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EVALUATION OF NORTHWEST PACIFIC TROPICAL CYCLONE TRACK FORECAST DIFFICULTY AND SKILL AS A FUNCTION OF ENVIRONMENTAL STRUCTURE

by

Benny H. Webb

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Thesis Co-Advisors: Russell L. Elsberry
Lester E. Carr III

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A Systematic Approach for tropical cyclone track forecasting by Carr and Elsberry defines the Synoptic Environment of each cyclone in terms of ten Synoptic Pattern/Region combinations. Because storms in each Pattern/Region combination have characteristic tracks that are dramatically different, it is hypothesized that the degree of difficulty in forecasting the tropical cyclone track, and the skill of the Joint Typhoon Warning Center (JTWC) track forecasts will be a function of the Synoptic Environment. The degree of forecast difficulty is defined by comparing forecast track errors (FTEs) of the operational CLImatology and PERsistence (CLIPER) technique in each of the ten Pattern/Region combinations with the overall CLIPER FTEs. The most difficult combinations are the recurving scenarios of Weakened Ridge Region of the Standard Pattern and the Southerly Flow Region of the Multiple tropical cyclone Pattern. The least difficult combinations are the Dominant Ridge Regions of the Standard and Gyre Patterns. The JTWC forecasts have statistically significant skill compared to the no-skill CLIPER forecasts for storms in the Standard/Dominant Ridge and North-oriented Pattern/North-Oriented Region, which comprise nearly 77% of the five-year sample of JTWC forecasts. As transitions occur between the Synoptic Pattern/Region combinations, the degree of forecast difficulty increases, and the JTWC forecast skill decreases. Although the JTWC track forecasts are generally slow and slightly to the left, significant differences are found in many of the Pattern/Region combinations.

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Benny H. Webb
Lieutenant Commander, United States Navy
B.S., Eastern Kentucky University, 1982

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Author: Benny H. Webb

Benny H. Webb

Approved by: Russell L. Elsberry

Russell L. Elsberry, Thesis Co-advisor

Lester E. Carr III

Lester E. Carr III, Thesis Co-advisor

R L Haney

Robert L. Haney, Chairman
Department of Meteorology

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A Systematic Approach for tropical cyclone track forecasting by Carr and Elsberry defines the Synoptic Environment of each cyclone in terms of ten Synoptic Pattern/Region combinations. Because storms in each Pattern/Region combination have characteristic tracks that are dramatically different, it is hypothesized that the degree of difficulty in forecasting the tropical cyclone track, and the skill of the Joint Typhoon Warning Center (JTWC) track forecasts will be a function of the Synoptic Environment. The degree of forecast difficulty is defined by comparing forecast track errors (FTEs) of the operational CLImatology and PERsistence (CLIPER) technique in each of the ten Pattern/Region combinations with the overall CLIPER FTEs. The most difficult combinations are the recurving scenarios of Weakened Ridge Region of the Standard Pattern and the Southerly Flow Region of the Multiple tropical cyclone Pattern. The least difficult combinations are the Dominant Ridge Regions of the Standard and Gyre Patterns. The JTWC forecasts have statistically significant skill compared to the no-skill CLIPER forecasts for storms in the Standard/Dominant Ridge and North-oriented Pattern/North-Oriented Region, which comprise nearly 77% of the five-year sample of JTWC forecasts. As transitions occur between the Synoptic Pattern/Region combinations, the degree of forecast difficulty increases, and the JTWC forecast skill decreases. Although the JTWC track forecasts are generally slow and slightly to the left, significant differences are found in many of the Pattern/Region combinations.

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Last but not least, I would like to acknowledge my dad, the late Rev. R. V. Webb, who has proven to me many times during my life that anything is possible with a little faith and hard work.

I. INTRODUCTION

A. TROPICAL CYCLONE TRACK FORECASTING

The accurate forecasting of tropical cyclone (TC) movement is vital for a large portion of the world. The continuing effort of tropical meteorologists to reduce the forecast errors of TC movement is driven by the deadly consequences to lives, ships, businesses, and homes if mistakes are made in the forecast movement of a TC. Objective track prediction aids and numerical weather prediction models are viewed as the primary tools to provide improved integrated TC track and structure forecasts. However, the models may have systematic errors in TC track forecasts. The forecaster's knowledge gained through experience is also an invaluable tool. The combination of numerical models, objective aids, and experience-gained knowledge can vary greatly between warning centers and individual forecasters. Consequently, the temporal consistency of official forecasts may be degraded, and may not improve upon objective forecasts as expected (Elsberry and Dobos 1990).

The area of study for this thesis is the western North Pacific, where the Joint Typhoon Warning Center (JTWC) in Guam is responsible for forecasting tropical cyclones. The official TC track errors discussed will be from JTWC. The ultimate goal for JTWC is to reduce their overall forecast track error (FTE), which is defined (Fig. 1--end of chapter) to be the absolute distance between the forecast position and the verifying ("best track") position based on careful post-storm analysis. The long-term goal is to reduce JTWC FTEs from 120, 240, and 360 n mi to 50, 100, and 150 n mi at the forecast times of 24, 48, and 72 h, respectively.

"Dangerous semi-circles" are defined areas that Navy ships must avoid. These areas include the likely track uncertainty surrounding the TC and are determined by the long-term

average FTEs of the official JTWC forecasts for the North Pacific. Every storm is treated as having the same FTEs for the respective dangerous semi-circles (i.e., the radii of 120, 240, and 360 n mi are added to the 35 kt wind radii at forecast times of 24, 48, and 72 h, respectively). These semi-circles are extremely important to ships, shore installations, and aircraft. U.S. Navy ships are required by Pacific Fleet Commanders to remain outside these dangerous semi-circles. However, these standard radii for the dangerous semi-circles could be reduced if track forecasts were more accurate.

This requirement for JTWC to forecast more accurately was the motivation for Carr and Elsberry (1994; hereafter CE) to introduce the Systematic and Integrated Approach to Tropical Cyclone Track Forecasting, which will hereafter be referred to as the Systematic Approach. Because this thesis addresses TC track forecast errors in the framework of the Systematic Approach, it will be briefly described here. Complete details are provided by CE and Carr *et al.* (1995).

The Systematic Approach is intended to provide a consistent procedure for formulating the official forecast to minimize errors. A key requirement for successful application of the Systematic Approach is that the forecaster must have a reasonably comprehensive knowledge of how the numerical track forecast guidance tends to err in various recurring meteorological situations. These situations are characterized in terms of Environmental Structure, which must fall into one of ten Synoptic Pattern and Region combinations.

B. ENVIRONMENT STRUCTURE

The Environmental Structure of western North Pacific tropical cyclones must fall into one of the four Synoptic Patterns (Table 1) defined in the Systematic Approach by CE. The Synoptic Patterns are comprised of the large-scale circulation features including adjacent cyclones and anticyclones. The Synoptic Patterns are conceptual models based on NOGAPS streamline and isotach analyses primarily at 500 mb. The structure and orientation of the mid-tropospheric subtropical ridge is the prominent feature in many of the conceptual models. In addition, the TC lies in a smaller Synoptic Region (Table 1) within the Synoptic Pattern, such that the environmental steering associated with this Synoptic Pattern/Region combination is the primary determinant of the storm motion. As indicated above, only a brief summary of the Synoptic Patterns and Regions will be provided here.

Table 1. Synoptic Pattern/Region combinations (with abbreviations) that characterize the Environment Structure in the Systematic Approach (see descriptions in CE).

Patterns	Regions
S - Standard	DR - Dominant Ridge WR - Weakened Ridge AW - Accelerating Westerlies
N - North Oriented	NO - North-Oriented AW - Accelerating Westerlies
G - Monsoon Gyre	DR - Dominant Ridge NO - North-Oriented AW - Accelerating Westerlies
M - Multiple TCs	NF - Northerly Flow SF - Southerly Flow

1. Standard Synoptic Pattern

The Standard (S) Synoptic Pattern is identified when the axis of the subtropical ridge influencing the steering of the TC is approximately east-west, although it may be slightly tilted longitudinally. In the idealized pattern (see Fig. 3.17 in CE), this east-west oriented subtropical ridge separates the tradewind easterlies and the mid-latitude westerly flow. In nature, the ridge structure may be modulated by the passage of a midlatitude ridge or a trough that introduces a "break" in the ridge.

Three Synoptic Regions are defined in the S Pattern (Table 1). The DR Region is poleward of the equatorial trough and equatorward of the subtropical ridge. The TCs in the S/DR region tend to have long, predominantly westward tracks as in Fig. 2a. A separate small Synoptic Region called Weakened Ridge (WR) satisfies two location criteria of being east of, and close to, the subtropical ridge break and being in a relatively weak (5-8 kt), southeasterly-to-southerly environmental steering. Short, poleward tracks are associated with the S/WR combination (Fig. 2b) as TCs move through the subtropical ridge. Finally, the Accelerating Westerlies (AW) Synoptic Region is poleward of the subtropical ridge and east of the ridge break. One typical sequence for TC movement is to recurve from the WR Region into this AW Region, in which tracks (Fig. 2c) are first northward and then accelerate northeastward. Because the recurvature may occur at low latitudes in early- or late-season TCs, the initial point of these AW Region storms has a large latitudinal variation, and the tracks may be quite long or quite short depending on how soon after recurvature that dissipation occurs.

2. North-Oriented Synoptic Pattern

The North-oriented (N) Synoptic Pattern (see Fig. 3.21 in CE) has the following conditions for classification: (i) a significant break in the subtropical ridge must be present poleward of the TC; and (ii) a prominent, and primarily north-south oriented, ridge exists to the east of the ridge break that also extends significantly equatorward of the latitude of the TC. The monsoon trough axis also becomes oriented southwest-to-northeast in this Pattern.

Two Synoptic Regions are defined in the N Pattern (Table 1). The NO Region is to the east of the reverse-oriented monsoon trough and extends to a col region near the poleward edge of the subtropical ridge. Small TCs typically form in the cyclonic shear of the NO Region, and then have a predominantly poleward track (Fig. 3a) with large variations. These poleward tracks are quite different from those in the S/WR Pattern/Region because the synoptic environment is much different. The second Region within the N Pattern is the AW Region, which is analogous to the S/AW Pattern/Region. If the TC recurves at low latitudes, the track direction (Fig. 3b) while in N/AW may actually be more poleward than in the S Pattern.

3. Gyre Synoptic Pattern

The Monsoon Gyre (G) Synoptic Pattern (see Fig. 3.25 in CE) requires: (i) there is present in the vicinity of the TC a particular type of monsoonal circulation that will hereafter be termed a monsoon gyre (MG); and (ii) the TC has a position relative to the MG that its steering is directly influenced by the MG.

The G Pattern contains three Regions (Table 1). The NO and AW Regions are essentially the same as previously described for the N and S Patterns. The G/DR Region is

the region to the northwest of the MG where east-northeasterly steering occurs due to the gradient between the MG and the ridge to the north. Storms in the G/NO Pattern/Region (Fig. 4a) usually have cyclonically curved tracks at the beginning. Some of these tracks can be quite long, which indicates that the monsoon gyre circulation persisted for some time. Near the poleward side of the MG, the tracks will become G/DR (Fig. 4b) or G/AW (Fig. 4c) depending on the westward motion or northward motion, respectively. It is clear from Figs. 4b and 4c that a large difference in tracks occurs depending on how the TC passes through the bifurcation point at the poleward end of the G/NO Pattern/Region. The potential for large track errors in this region could be expected.

4. Multiple Tropical Cyclone Synoptic Pattern

The Multiple TC (M) Pattern (see Fig. 3.28 in CE) is identified when two TCs are: (i) in proximity to each other (less than about 20 degrees lat.), but with a separation distance that would not result in significant binary interaction, which generally occur at less than 10-12 degrees lat. (Brand 1970; Dong and Neumann 1983); (ii) oriented approximately east-west; and (iii) sufficiently close (north or south) to the ridge axis that the height gradient between the western (eastern) TC and the eastern (western) ridge circulation subjects the eastern (western) TC to moderately strong (10-15 kt) and predominantly poleward (equatorward) steering flow. However, it is possible for additional TCs to be in proximity without setting up competing M Synoptic Patterns.

The M Pattern contains the Southerly Flow (SF) and Northerly Flow (NF) Synoptic Regions that are symmetric about a north-south line running through the centroid between the TCs. The SF (NF) Region consists of locations that are: (i) in the predominantly

southerly (northerly) environmental flow in the vicinity of the line running from the center of the western (eastern) TC to the center of the eastern (western) ridge circulation; and (ii) no closer than about 10 degrees lat. to the western (eastern) TC.

Within the SF Region, a TC will move through the recurvature point (see Fig. 3.28 in CE) into the AW Region at a more rapid than normal translation speed. Although this eastern TC would have an apparent cyclonic rotation relative to the western TC, it is emphasized that this multiple TC interaction is not a Fujiwhara-type effect as the separation distance is too large for the eastern TC to be embedded in the western TC's circulation.

The NF Region of the M Pattern will have a steering flow that opposes the expected poleward and westward beta-effect propagation (see CE for details). Consequently, a TC in the NF Region will tend to have a westward and either small poleward or equatorward drift depending on the relative strengths of the two opposing effects. Thus, the TC in the NF Region may transition to the DR Region of the anticyclone to the west. If the TC is large and near the poleward end of NF Region, it may transition to the AW Region, which is considered to be part of the Standard (S) Pattern rather than the M Pattern. These M Patterns are not expected to exist very long as the conditions regarding separation distance and the favorable positions relative to the anticyclones to the east or west do not persist.

Storm tracks from 1989-93 (Fig. 5) confirm these expectations. Tracks in the SF Region (Fig. 5a) of the M Pattern are consistent with the expected north-northwestward flow between a western TC and an anticyclone cell to the east. Although not indicated by these tracks, the translation speeds of the TCs are larger than expected for a TC approaching the subtropical ridge axis. Tracks in the NF Region (Fig. 5b) are primarily westward and

equatorward. In the equatorward (westward) cases, the environmental steering effect dominates (is neutralized by) the beta-effect propagation, which is westward and poleward. However, one southeastward track near Japan is north of the ridge and has a TC to the northeast. As indicated by the small number of tracks, not many cases exist in the five-year sample. However, the anomalous translation speed in the SF Region and anomalous track directions in the NF Region make it important that the forecaster recognize this Environment Structure.

The tracks for the various Pattern/Region combinations (Figs. 2 through 5) illustrate some of the dramatic differences in motion. These track differences emphasize the importance of identifying accurately the Environment Structure in the Systematic Approach. One of the basic premises of this work is that the track forecast errors will be different for the various Pattern/Region combinations, and that knowledge of these differences can be used to improve the forecast and warning system.

C. OBJECTIVES

The first objective will be to demonstrate that different tracks (Figs. 2 through 5) for the different Synoptic Pattern/Regions have different degrees of difficulty. This will be accomplished by comparing the operational CLImatology and PERsistence (CLIPER) forecast errors (FTE) in separate Pattern/Regions with the overall CLIPER FTEs. This will demonstrate the usefulness of Synoptic Pattern/Region classifications. These CLIPER forecasts may also be used as a measure of skill for each Pattern/Region combination.

The second objective of this thesis is to demonstrate that within certain Pattern/Region combinations described by the Systematic Approach, Joint Typhoon Warning Center (JTWC)

warnings have significant skill (no skill) as measured against CLIPER. Once this skill (no skill) has been identified for the Pattern/Region combinations, the degree of confidence to be placed in those forecasts should be higher (lower) than for the overall average JTWC forecast. This information could then be used in varying the size of the dangerous semicircle for ships, or in decreasing the over-warning of an area, and thus would save monetary resources in unnecessary ship deployments or shore-based preparations while also increasing customer confidence in the official warnings.

The third objective is to demonstrate that the degree of forecast difficulty increases dramatically during a transition from one Pattern/Region combination to another Pattern/Region combination. Also, it will be demonstrated JTWC forecast skill will decrease when the TCs are approaching, during, and after a transition. Large JTWC Forecast Track Errors (FTEs) are expected to occur during the transition times since the forecaster does not always know what, if any, transition will occur within the next three days of the forecast period.

The fourth and final objective is to show that directionality of the JTWC track forecasts is a function of the Synoptic Environment, i.e., certain Pattern/Region combinations may show a consistent left or right of track bias, or may be slow or fast as compared to the verifying best track position of the TC. One purpose of evaluating the directionality of JTWC forecast warnings is to determine if these new error ellipses, derived from the respective Pattern/Region combinations, can replace the standard circular error radii currently being used for all of the tropical cyclones in the western North Pacific.

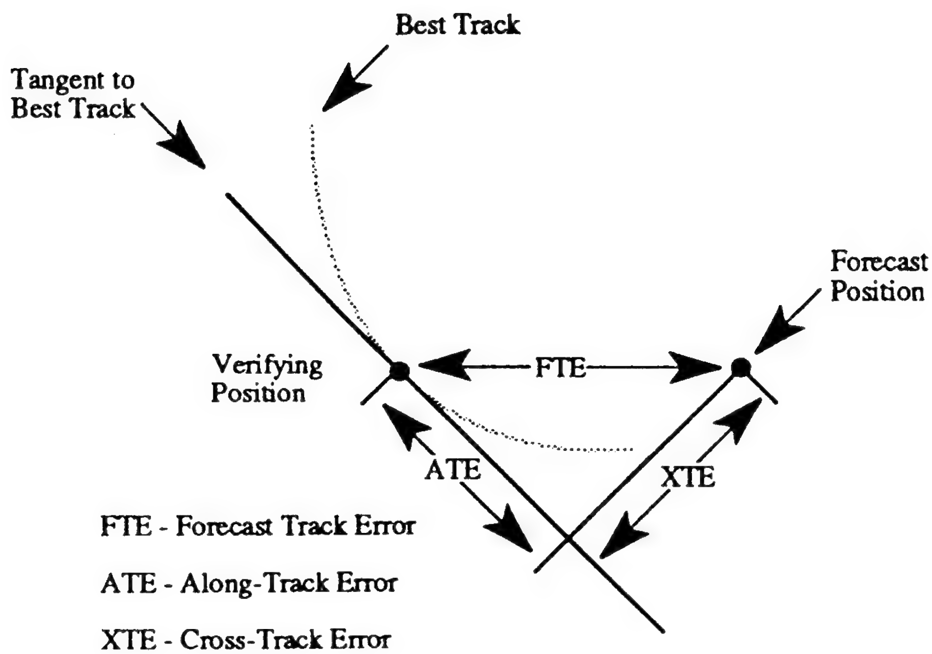

Figure 1 Definition of cross-track error (XTE), along-track error (ATE), and forecast track error (FTE). In this example, the XTE is positive (to the right of the best track) and the ATE is negative (behind or slower than the best track) (ATCR 1993).

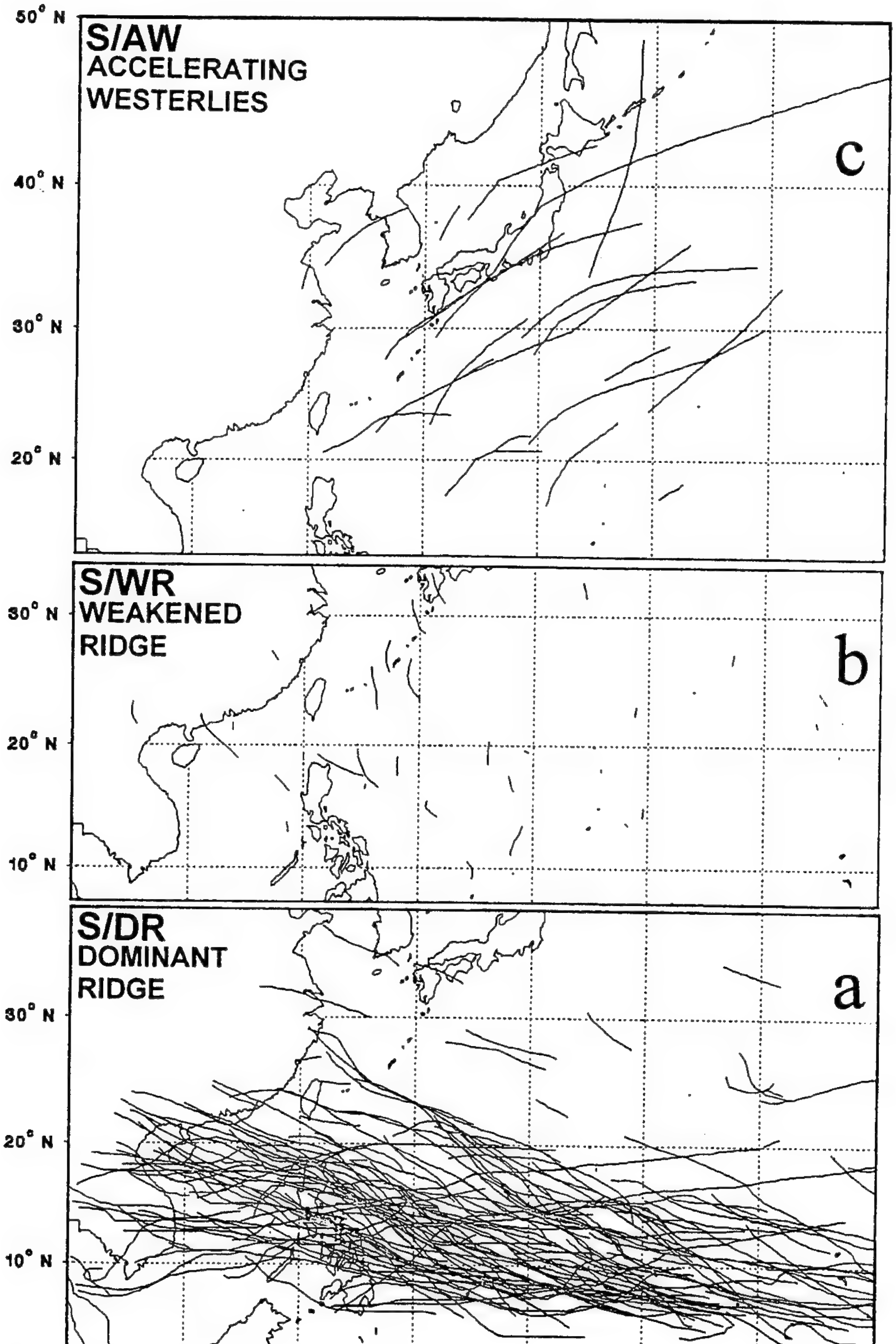

Figure 2 Storm tracks during 1989-1993 while the storm is in the Standard Pattern and the (a) Dominant Ridge, (b) Weakened Ridge, and (c) Accelerating Westerlies Regions (Carr *et al.* 1995).

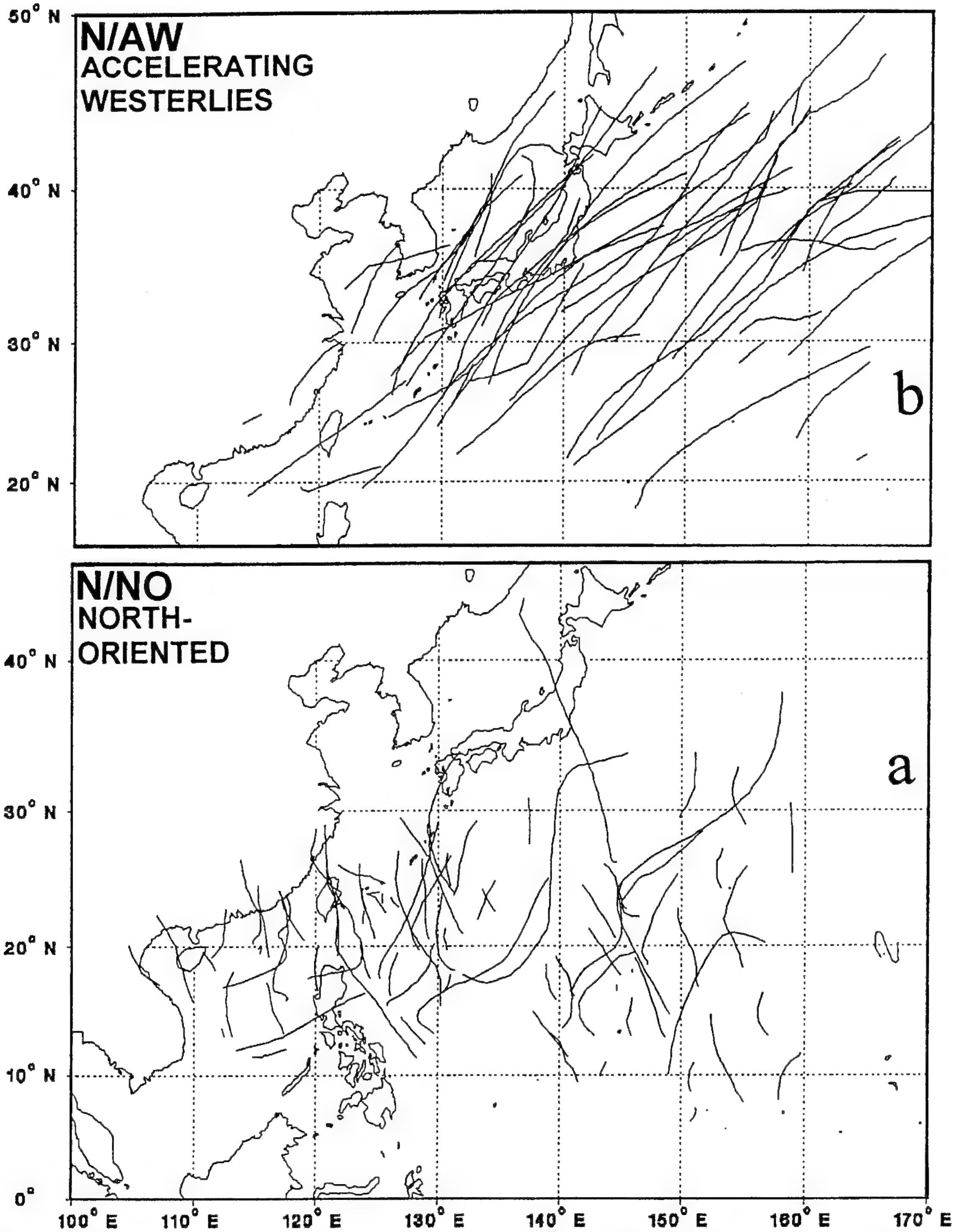

Figure 3 Storm tracks as in Fig. 2, except in the North-oriented Pattern and the (a) North-oriented and (b) Accelerating Westerlies Regions (Carr *et al.* 1995).

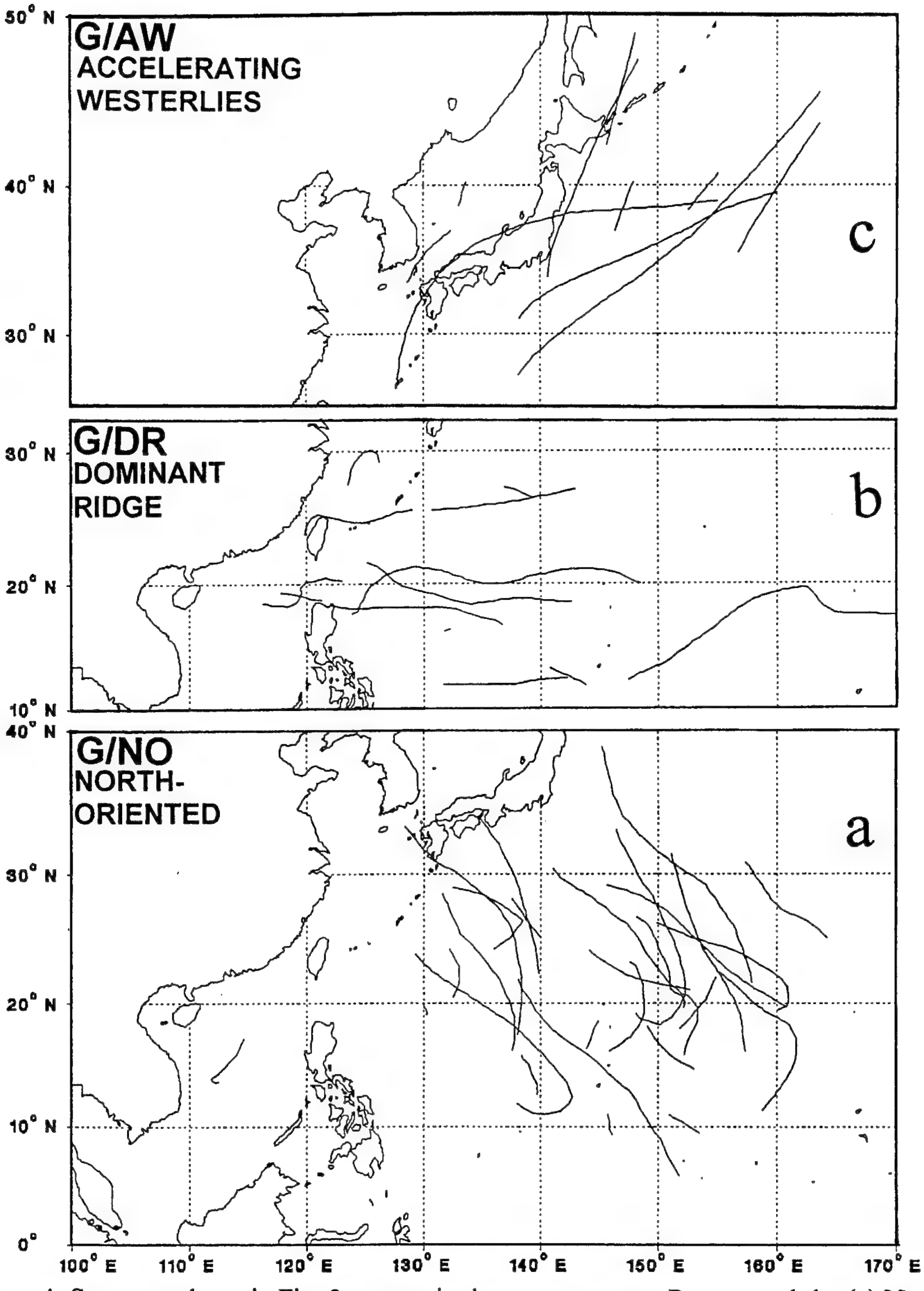

Figure 4 Storm tracks as in Fig. 2, except in the monsoon gyre Pattern and the (a) North-oriented, (b) Dominant Ridge, and (c) Accelerating Westerlies Regions (Carr *et al.* 1995).

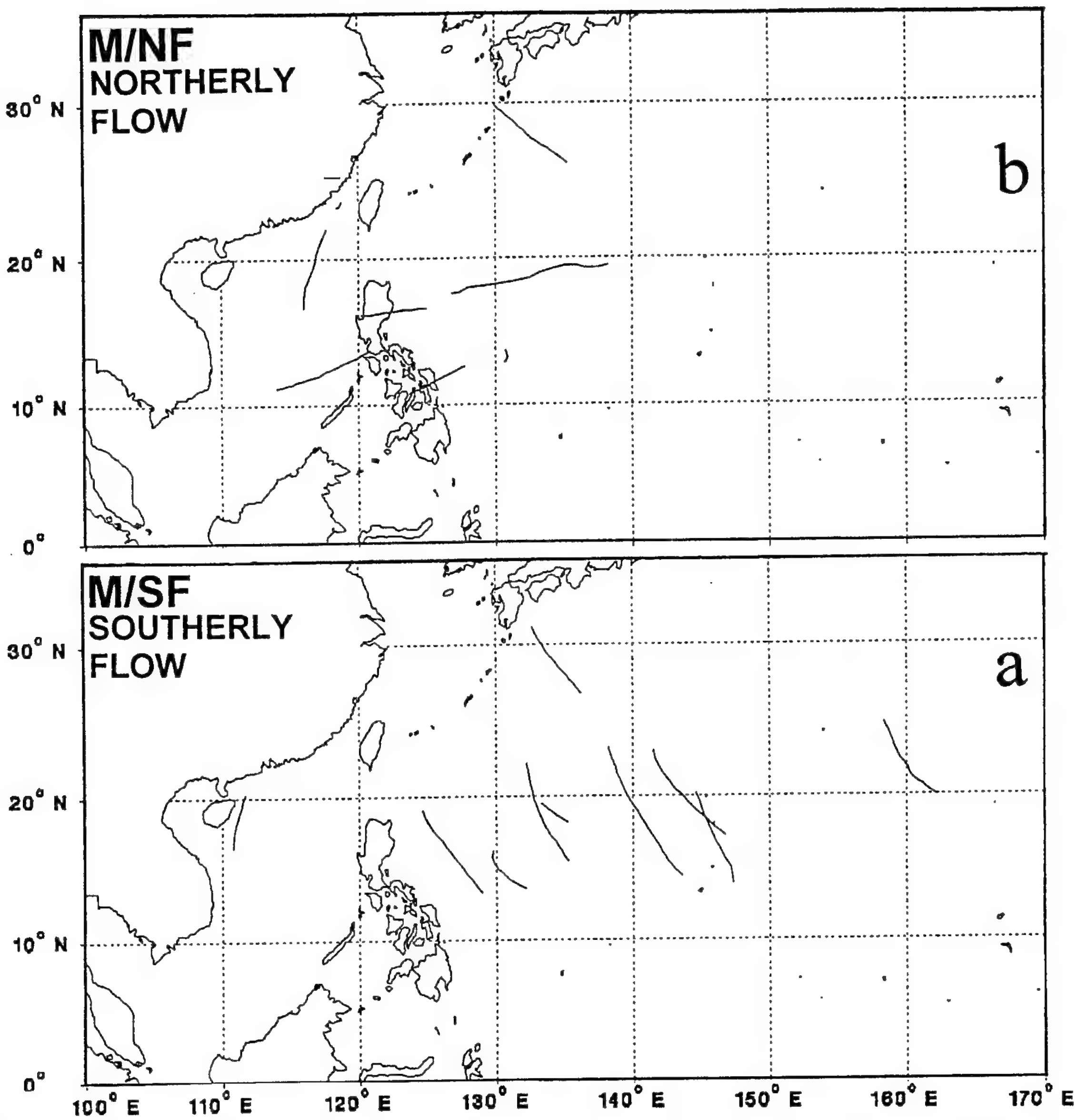

Figure 5 Storm tracks as in Fig. 2, except in the multiple storm Pattern and the (a) Southerly Flow and (b) Northerly Flow Regions (Carr *et al.* 1995).

II. METHODOLOGY

Carr *et al.* (1995) examined five years (1989-1993) of the 12-h Naval Operational Global Atmospheric Prediction System (NOGAPS) 500 mb analyses of streamlines and isotachs for all dates on which a TC existed in the western North Pacific. Storm tracks were broken into track segments that were categorized according to the Synoptic Patterns and Synoptic Regions of the Systematic Approach. A total of 166 storms during the five years resulted in 2485 Pattern/Region assignments. Of the 166 storms, only 43 remained in a particular Pattern/Region for their entire existence (39 in S/DR, three in G/NO, and one in G/DR).

Forecast Track Errors (FTEs) were calculated using the Automated Tropical Cyclone Forecasting (ATCF) system error routines for all forecasts with the initial time in each Pattern/Region combination. The sample includes all forecasts from the initial warning time to the last one that could be verified with the last official JTWC warning for that storm. Although additional positions beyond the end of the JTWC warnings may be available for a tropical cyclone undergoing extratropical transitions, these positions were not used to verify the forecasts because responsibility for those extratropical positions has been passed to another agency. Forecasts that began within the specified Pattern/Region combination were continued to be verified even if the storm had transitioned to another Pattern/Region combination, as long as the verifying time was on or before the JTWC final warning.

The ATCF statistics program calculates various track errors and includes mean forecast track error (FTE), mean cross-track (XTE), mean along-track error (ATE), mean speed error (SPD), and the corresponding standard deviations (STD) for each of these errors.

The ATCF statistics program also compares FTEs from two objective aids (e.g., JTWC vs CLIPER, or NOGAPS vs CLIPER) in such a way that the initial times and the verifying times are identical for both techniques. That is, such comparisons are for homogeneous samples.

Mean FTEs were also calculated before, during, and after transitions from one Pattern/Region combination to another. Transition time was defined to be the Date Time Group (DTG) at which the storm had fully transitioned from a Pattern/Region combination to another Pattern/Region combination. Such transitions can proceed rapidly so that the Pattern/Region change occurs between consecutive synoptic times, or proceed slowly so that the Environmental Structure is in a transitional state spanning one or more synoptic times. The "before" period begins 72 h before the transition time and the "after" period continues 48 h after transition time. In many Synoptic Patterns, the storm may not have been in the same Region for 72 h prior to the transition. Only those forecasts in the same Pattern/Region leading up to the specific transition are included. Thus, the number of forecasts tends to fall off at times well before the transition. The number of verifying forecasts following the transition also decreases if the verifying time is beyond the last JTWC warning time for that storm. In this case, a verifying forecast will continue to be included even after the storm has undergone another transition.

III. DEGREE OF DIFFICULTY

The CLIPER track forecast technique has been used as a standard to measure the skill of the official and objective aid track forecasts (Elsberry 1995). The western North Pacific CLIPER is a set of regression equations for the 12, 24, 36, 48, and 72 h displacements in the meridional and longitudinal directions. Predictors that are entered include the present and the past 12 h and 24 h positions, the present intensity, and the Julian date. This thesis uses the operational CLIPER forecasts by JTWC, so that the warning position and the past 12 h and 24 h positions are from the "working best track," rather than from a post-storm analysis (best track) that would be more accurate. Notice that no meteorological fields are required for application of CLIPER. Thus, the meteorology value-added (skill) of track forecast techniques may be measured by their improvement over the CLIPER track forecast. Elsberry (1995) illustrates the normalization of forecast track errors (FTE) of official and objective aids by the CLIPER FTEs.

The first objective here of comparing CLIPER mean FTE within a specific Pattern/Region [CLIPER (P/R)] to the five-year (1989-1993) CLIPER mean FTE [CLIPER (ALL)] is to document that the different storm tracks in the various Synoptic Pattern/Region combinations (Figs. 2, 3, 4, and 5) have different "degrees of difficulty." That is, characteristic storm tracks that have larger (smaller) CLIPER FTEs are said to be more (less) difficult to forecast. Documentation of more/less difficult storm forecasts in different Pattern/Region combinations is useful to the JTWC forecaster, and to the warning system customer (who may be alerted to potentially larger/smaller errors). In addition, this documentation will serve as an indirect validation that is useful to characterize the different

Environment Structures in terms of Synoptic Pattern/Regions as proposed by CE in the Systematic Approach. Finally, the different CLIPER (P/R) FTEs become a better measure of skill or no skill within that Pattern/Region, compared to the use of the CLIPER (ALL) as a skill measure for all storms.

Graphs were created for each Synoptic Pattern/Region comparing mean FTEs of the operational CLIPER (P/R) forecasts and the mean CLIPER (ALL) FTE at 12, 24, 36, 48, and 72 h. Negative (positive) FTE [CLIPER (P/R) minus CLIPER (ALL)] differences indicate the FTE for CLIPER (P/R) is less (more) than for CLIPER (ALL), and therefore is less (more) difficult to forecast than the average western North Pacific tropical cyclone. To determine if the mean CLIPER FTEs from specific Pattern/Region combinations are equal (i.e., statistically no difference) or not equal (i.e., statistically different) from the mean CLIPER (ALL) FTE for the five year period, a two-sided *t*-test with a confidence level of 95% will be used,

$$t_{(n-1)} = \frac{\bar{x}_{P/R} - \mu_{ALL}}{s_{P/R} \,/\, \sqrt{n_{P/R}}} \quad . \qquad (1)$$

This *t*-test will compare a subsample mean [CLIPER (P/R) FTE; $\bar{x}_{P/R}$] with the population mean [CLIPER (ALL) FTE; μ_{ALL}] and determine if the mean FTEs are statistically different, given the subsample standard deviation $s_{P/R}$ and the subsample size $n_{P/R}$ with $(n_{P/R} - 1)$ degrees of freedom. This determination based on the two-sided *t*-test greatly reduces the likelihood that it is simply random errors that are causing the mean FTE differences that are displayed in the graphs.

Fewer 12 h and 36 h forecasts are available than for 24, 48, and 72 h, because JTWC only started producing the 12 h and 36 h forecasts in 1992. Thus, only two of the five years of the data base include these forecasts. Where the number of cases falls below 10, the comparisons are usually not considered reliable or representative of the sample.

Two classification of FTEs were defined for each Pattern/Region combination.

- Intra-Synoptic: FTEs for those TCs that stay within the same Pattern/Region throughout the 12, 24, 36, 48, and 72 h forecast period.
- Inter-Synoptic: FTEs for those TCs that begin within the specified Pattern/Region but the verification time of the forecast is allowed to be after a transition to another Pattern/Region

The differences in FTE verifications between the two definitions are illustrated in Fig. 6 (figures grouped at end of chapter). Inter-Synoptic forecasts were used for this comparison because the forecaster knows the Synoptic Pattern/Region at the initial time, but may not know whether a transition will occur or when it will occur within the 72 h forecast interval. Thus, the CLIPER (P/R) FTE for the Inter-Synoptic cases are more representative of actual degree of difficulty. These degree of difficulty comparisons will first be made within the four Synoptic Patterns (S, N, G, and M), and then will be combined to rank order the degree of difficulty for all the Pattern/Region combinations.

A. STANDARD SYNOPTIC PATTERN

Storms in the Dominant Ridge (DR) Synoptic Region of the Standard (S) Pattern are judged to be less difficult to forecast since the mean FTE differences relative to the overall CLIPER FTE are all negative for the five forecast times (Fig. 7). Since tracks in the S/DR

Region (Fig. 2a) are generally westward with consistent speeds, these forecasts are relatively easier. Although the CLIPER FTEs for the S/DR storms are only slightly smaller (24 n mi at 72 h) than for the overall CLIPER, the FTEs steadily increase with time and are statistically different as determined by the two-sided *t*-test (Table 2). The large sample sizes (834 or greater) explain why these relatively small FTE differences (-4, -9, -15,-17, and -24 n mi at 12, 24, 36, 48, and 72 h, respectively) are statistically different from zero (i.e., mean FTEs of CLIPER (S/DR) and CLIPER (ALL) are not equal). Notice also that the standard deviations of the FTEs for the S/DR storms are smaller than for CLIPER (ALL), which

Table 2. Statistical summary of the CLIPER (S) vs CLIPER (ALL) comparison. The *t*-test values (* indicates the *t* value is statistically significant) for each Region of the S Synoptic Pattern are calculated from two-sided *t*-test (Eq. 1) based on the sample mean ($\bar{x}_{P/R}$) and standard deviation ($s_{P/R}$) of the forecast track errors (FTEs) in n mi and number of cases ($n_{P/R}$).

	Forecast Period				
	12 h	**24 h**	**36 h**	**48 h**	**72 h**
CLIPER (ALL)					
μ_{ALL}	79	123	192	242	359
s_{ALL}	54	79	117	146	208
n_{ALL}	1494	3623	1271	3025	2469
S/DR					
t-test	-2.379*	-5.664*	-4.247*	-5.490*	-5.248*
$\bar{x}_{S/DR}$	75	114	177	225	335
$s_{S/DR}$	51	72	102	133	183
$n_{S/DR}$	920	2053	834	1845	1601
S/WR					
t-test	-1.257	0.743	1.334	1.334	2.763*
$\bar{x}_{S/WR}$	71	128	227	268	495
$s_{S/WR}$	45	83	166	187	348
$n_{S/WR}$	50	152	40	92	50
S/AW					
t-test	1.424	-0.306	N/A	N/A	N/A
$\bar{x}_{S/AW}$	98	118			
$s_{S/AW}$	64	88			
$n_{S/AW}$	23	29			

indicates these storm tracks are probably more consistent A second statistical *t*-test called the one-sided *t*-test was also calculated that treated CLIPER (S/DR) and CLIPER (ALL) as two samples rather than a sample and a population. Only the 12 h FTE difference of -4 n mi was determined to not be statistically significant, whereas the mean FTEs of CLIPER (S/DR) and CLIPER (ALL) were statistically different for the remaining forecast periods (24, 36, 48, and 72 h). The S/DR Pattern/Region was the only Synoptic Pattern/Region for which the sample sizes for CLIPER were large enough to use this second statistical test.

Storms in the Weakened Ridge (WR) and Accelerating Westerlies (AW) Regions of the Standard (S) Pattern are more difficult to forecast than the "typical" tropical cyclone since the mean CLIPER FTEs for storms in these Regions are generally larger than the five-year mean CLIPER (Fig. 7). In addition, the standard deviations of the FTEs for the S/WR and S/AW storms are larger than for the CLIPER (ALL) FTEs, especially for the 72 h forecasts in the S/WR combination (Table 2). Compared to the S/DR, a relatively small number of forecasts are available for storms in the S/WR combination. Tracks in the S/WR Region (Fig. 2b) are usually short lived, so the forecasts verifying beyond 24 hours normally follow a transition to the S/AW or back to the S/DR Pattern/Region combinations. The 12 h through 48 h mean FTE differences, as determined by the two-sided *t*-test (Table 2), are not statistically significant (i.e., the mean FTEs of CLIPER (S/WR) and CLIPER (ALL) are considered equal). However, when more data become available, these mean FTEs may become statistically different, if the mean FTEs do not dramatically change. The 72-h CLIPER FTE difference for storms in the S/WR combination is 136 n mi, which means an FTE of 495 n mi compared to the five-year mean of 359 n mi. This 72 h period FTE

difference is the only forecast period in the S/WR Pattern/Region that is statistically significant at the 95% confidence level. Such a large FTE difference implies a much more difficult 72-h forecast situation than normal, presumably because a subsequent transition to S/AW with acceleration toward the NE (Fig. 2c), or back to a westward track in S/DR. Indeed, this recurvature versus non-recurvature situation is a difficult forecast in many cases.

Few CLIPER forecasts verify beyond 24 h for storms in the S/AW Pattern/Region since TCs in S/AW are either dissipating or becoming extratropical cyclones (Fig. 2c). The 19 (-5) n mi CLIPER FTE difference at 12 (24) h for S/AW cases is for only 23 (29) cases, and thus is not statistically different as determined by the two-sided t-test (Table 2). However, when more data become available, the 12 h difference may become statistically significant if the mean CLIPER (P/R) FTE remains the same.

B. NORTH-ORIENTED SYNOPTIC PATTERN

Storms in the North-Oriented (NO) and AW Synoptic Regions of the North-oriented (N) Synoptic Pattern (Fig. 8) also have positive FTE differences relative to the five-year CLIPER, which again indicates storms in these Pattern/Regions are more difficult to forecast than the "typical" tropical cyclone. Although the CLIPER FTE differences for the N/NO storms are not very large (58 n mi at 72 h), the error growth trend is quite consistent from 24 h to 72 h. Given the large number of N/NO cases, all of these FTE differences are statistically significant as determined by the two-sided t-test (Table 3). Recall that the tracks in the N/NO combination (Fig. 3a) have considerable variability, which is consistent with these storms being more difficult to forecast than storms (e.g., in S/DR in Fig. 2a) that have more consistent track directions and speeds.

The CLIPER FTE differences for storms in the N/AW combination increase even more rapidly until 48 h (Fig. 8). All of these FTE differences are determined to be statistically different at the 95% confidence level (Table 3), except for 36 h which has too few cases (14) and a large standard deviation (189 n mi) for that forecast period. Although the decrease to 85 n mi at 72 h is for a sample size of only 17 cases, the standard deviation is only 144 n mi, and this CLIPER FTE difference is statistically significant according to the *t*-test (Table 3). The number of 72 h forecasts in the N/AW combination decreases because many of these storms will have dissipated by 72 h (Fig. 3b). Except for the $s_{N/AW}$ = 144 n mi, all of the other standard deviations for storms in the N Pattern are larger than for CLIPER (ALL). These larger means and standard deviations of the CLIPER FTEs thus alert the JTWC forecaster that a TC in the N Synoptic Pattern is more difficult to forecast.

Table 3. Statistical summary of the CLIPER (N) vs CLIPER (ALL) comparison as in Table 2, except for North-oriented (N) Synoptic Pattern.

	Forecast Period				
	12 h	**24 h**	**36 h**	**48 h**	**72 h**
CLIPER (ALL)					
μ_{ALL}	79	123	192	242	359
s_{ALL}	54	79	117	146	208
n_{ALL}	1494	3623	1271	3025	2469
N/NO					
t-test	-0.319	3.822*	2.948*	5.906*	4.733*
$\bar{x}_{N/NO}$	78	135	216	283	417
$s_{N/NO}$	54	83	131	164	242
$n_{N/NO}$	297	699	259	558	390
N/AW					
t-test	3.060*	5.854*	1.703	3.195*	2.434*
$\bar{x}_{N/AW}$	109	183	278	351	444
$s_{N/AW}$	74	107	189	196	144
$n_{N/AW}$	57	109	14	33	17

C. GYRE SYNOPTIC PATTERN

Tropical cyclones in the NO Synoptic Region of the Gyre (G) Synoptic Pattern have slightly positive FTE differences relative to CLIPER (ALL), which indicates they are more difficult to forecast than the "typical" TC (Fig. 9). Only the 24 h and 48 h forecast mean FTE differences are determined to be statistically different (Table 4). However, the variety of curved and straight-mover track segments for storms in the G/NO combination (Fig. 4a) are consistent with the more difficult track forecast assessment, even though the FTE difference at 72 h may not be statistically significant.

Storms in the DR Region of the G Synoptic Pattern have slightly negative FTE differences, which indicates these TCs are less difficult to forecast (Fig. 9). Notice that the $s_{G/DR}$ values are smaller than the s_{ALL} values (Table 4). However, the only mean CLIPER FTE difference in the G/DR combination that is statistically significant is the 48 h forecast (Table

Table 4. Statistical summary of the CLIPER (G) vs CLIPER (ALL) comparison as in Table 2, except for Gyre (G) Synoptic Pattern.

	Forecast Period				
	12 h	**24 h**	**36 h**	**48 h**	**72 h**
CLIPER (ALL)					
μ_{ALL}	79	123	192	242	359
s_{ALL}	54	79	117	146	208
n_{ALL}	1494	3623	1271	3025	2469
G/DR					
t-test	N/A	-1.734	N/A	-2.310*	-1.485
$\bar{x}_{G/DR}$		112		217	332
$s_{G/DR}$		74		121	189
$n_{G/DR}$		136		125	108
G/NO					
t-test	N/A	3.400*	N/A	2.427*	0.802
$\bar{x}_{G/NO}$		143		268	371
$s_{G/NO}$		93		153	188
$n_{G/NO}$		250		204	158

4). This lower degree of difficulty in the DR Region can be attributed to the TC tracks (Fig. 4b) that are normally east to west and have steady translation speeds as in S/DR.

The number of cases for AW Synoptic Region were only 3 (10) for the 12 (24) h forecasts, with no verifications for the 36, 48, and 72 h forecast periods. Therefore, no conclusions can be inferred from this sample.

D. MULTIPLE CYCLONE SYNOPTIC PATTERN

Storms in the Northerly Flow (NF) of the Multiple (M) Cyclone Synoptic Pattern have slightly negative FTE differences relative to CLIPER (ALL), while Southerly Flow (SF) Regions display slightly positive FTE differences through the 48 h forecast period (Fig. 10). However, storms in both Regions become more difficult to forecast at 72 h, as indicated by the 65 (110) n mi positive FTE differences for NF (SF) Synoptic Regions. The 72 h standard deviations of 280 and 319 n mi for M/NF and M/SF, respectively, are considerably larger than for s_{ALL} (Table 5). The 72 h mean FTE difference (110 n mi) of the SF Region is determined to be statistically significant at the 95% confidence level, while the 72 h mean FTE difference of the NF Region is not statistically significant, but is extremely close to the t value necessary for the chosen confidence level (Anderson and Sclove 1986). Storms in the M/SF combination are generally moving at larger translation speeds (Fig. 5a) than for the "normal" recurvature, which would be reflected in the climatology aspect of CLIPER. Storms in the M/NF combination have a wide variety of track directions (Fig. 5b), rather than a more uniform distribution as in the S/DR combination. While the persistence aspect of the CLIPER technique is dominant at early intervals, the variety of potential positions at 72 h makes the forecasts more difficult.

Table 5. Statistical summary of the CLIPER (M) vs CLIPER (ALL) comparison as in Table 2, except for Multiple Cyclone (M) Synoptic Pattern.

	Forecast Period				
	12 h	**24 h**	**36 h**	**48 h**	**72 h**
CLIPER (ALL)					
μ_{ALL}	79	123	192	242	359
s_{ALL}	54	79	117	146	208
n_{ALL}	1494	3623	1271	3025	2469
M/NF					
t-test	-3.336*	-1.811	-0.200	-0.407	1.983
$\bar{x}_{M/NF}$	61	110	187	235	424
$s_{M/NF}$	31	65	139	152	280
$n_{M/NF}$	33	82	31	78	73
M/SF					
t-test	0.108	1.056	0.736	0.996	2.040*
$\bar{x}_{M/SF}$	80	134	209	268	469
$s_{M/SF}$	54	82	120	177	319
$n_{M/SF}$	34	62	27	46	35

E. COMBINED DEGREE OF DIFFICULTY

The degree of difficulty based on the accuracy of the operational CLIPER over all of the 10 Synoptic Pattern/Region combinations may be summarized as in Fig. 11. This comparison is similar to Pike and Neumann (1987) in which they used CLIPER-type models in six tropical cyclone regions throughout the world to assess the difficulty of forecasting in each region. That is, the regions with the most difficult track forecasts are those that have the largest CLIPER track errors, while the regions with least difficult track forecasts are those that have the smallest CLIPER track errors. Applying this same approach for the Systematic Approach (Fig. 11), the S/WR and M/SF Pattern/Region combinations with the largest 72 h CLIPER FTEs (495 and 469 n mi, respectively) are considered to be the most difficult Pattern/Regions to forecast. The S/WR and M/SF Pattern/Region combinations are situations when the storm is recurving with the potential for high FTEs due to highly variable translation

speeds over the 72 h period. The G/DR and S/DR Pattern/Region combinations are considered to be the least difficult to forecast, since they have the smallest CLIPER FTEs (335 and 332 n mi, respectively) at 72 h. Storms in the DR Regions of the S and G Patterns usually have consistent translation speeds and have the characteristic east-to-west track, which is much easier to forecast than a recurving storm. Other Patterns/Regions that are considered difficult to forecast at 72 h are N/AW, M/NF, and N/NO, which all have larger operational CLIPER (P/R) mean FTEs than the CLIPER (ALL) mean FTE of 359 n mi.

The N/AW Pattern/Region is the most difficult to forecast at 24 h and 48 h because the mean CLIPER FTEs for these forecast periods (183 and 351 n mi, respectively) are larger than the overall CLIPER mean FTEs for those forecast times. This high degree of difficulty is expected since storms in the N/AW Pattern/Region have increased translation speeds and small errors in forecast translation speed of a storm can lead to large forecast errors, even after 24 to 48 h. Other Patterns/Regions that have larger mean FTEs at 24 h and 48 h than CLIPER (ALL) forecasts include G/NO, N/NO, M/SF, and S/WR. Although these Pattern/Region combinations are slightly more difficult to forecast at 24 h and 48 h than the "typical" tropical storm in the western North Pacific, the N/AW Pattern/Region CLIPER errors seem to be particularly large at 24 h and 48 h.

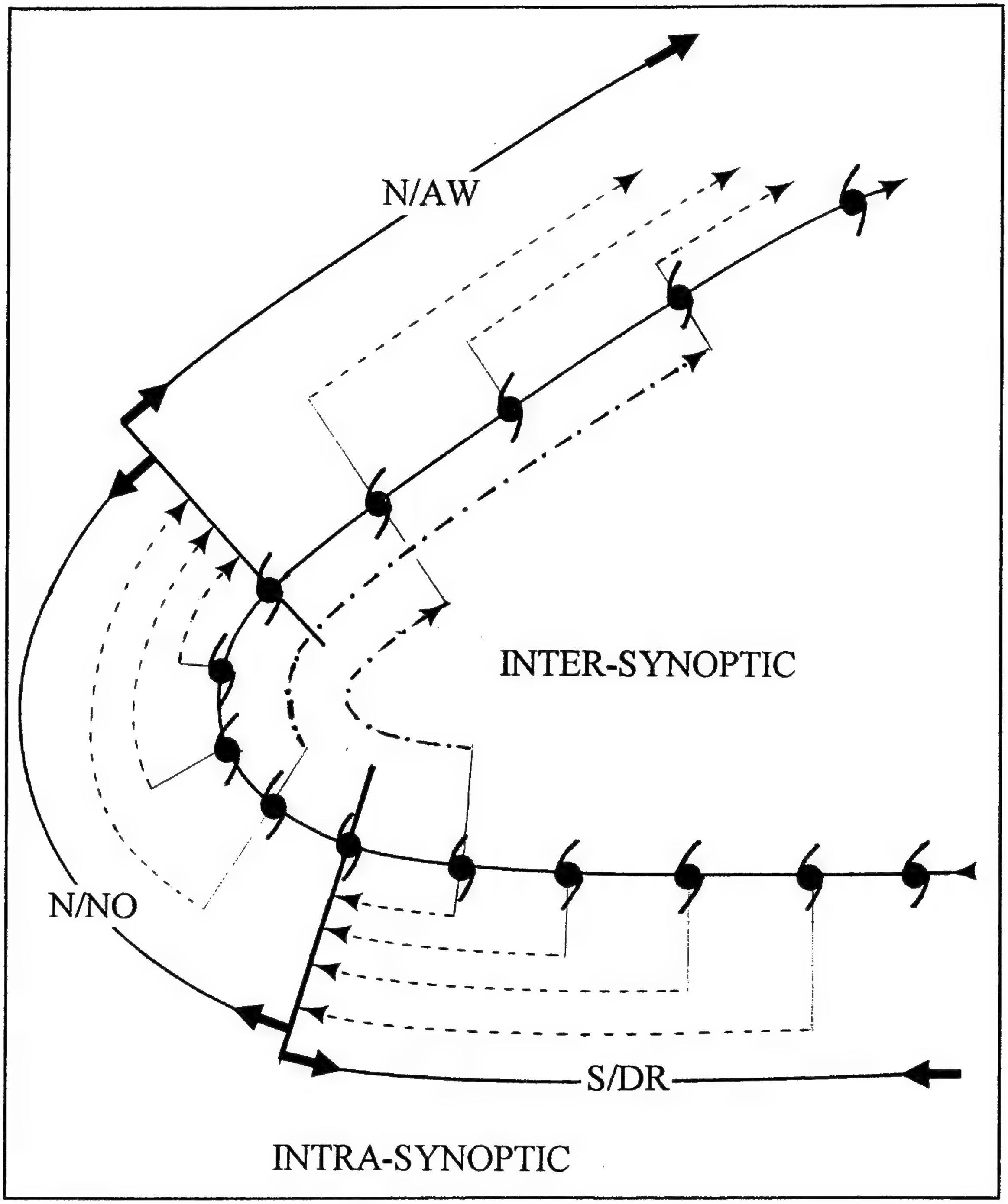

Figure 6 Definition of Intra-Synoptic and Inter-Synoptic classifications of Forecast Track Errors (FTEs). Intra-Synoptic are the FTEs of those tropical cyclones (TCs) that stay within the same Pattern/Region (P/R) through the forecast period (12 h to 72 h). Inter-Synoptic are the FTEs of the TCS that begin within the specified P/R, but verification time of the forecast is allowed to be after a transition to another P/R.

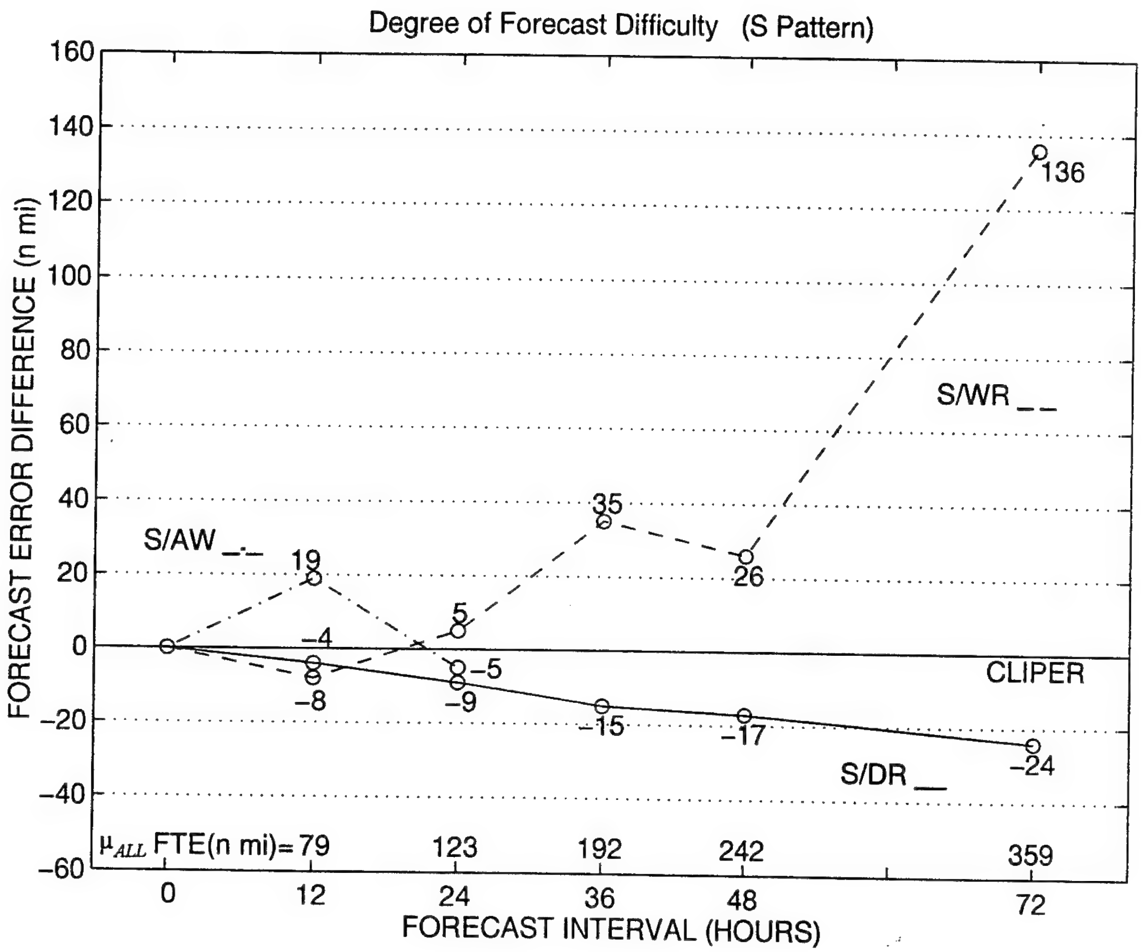

Figure 7 Degree of forecast difficulty of the Standard (S) Pattern. The CLIPER (ALL) FTEs (μ_{ALL}) are indicated at the bottom of the figure and the CLIPER FTE differences ($\bar{x}_{P/R} - \mu_{ALL}$) used in Eq. (1) are the values along the plot of each Pattern/Region combination. See Table 2 for further details.

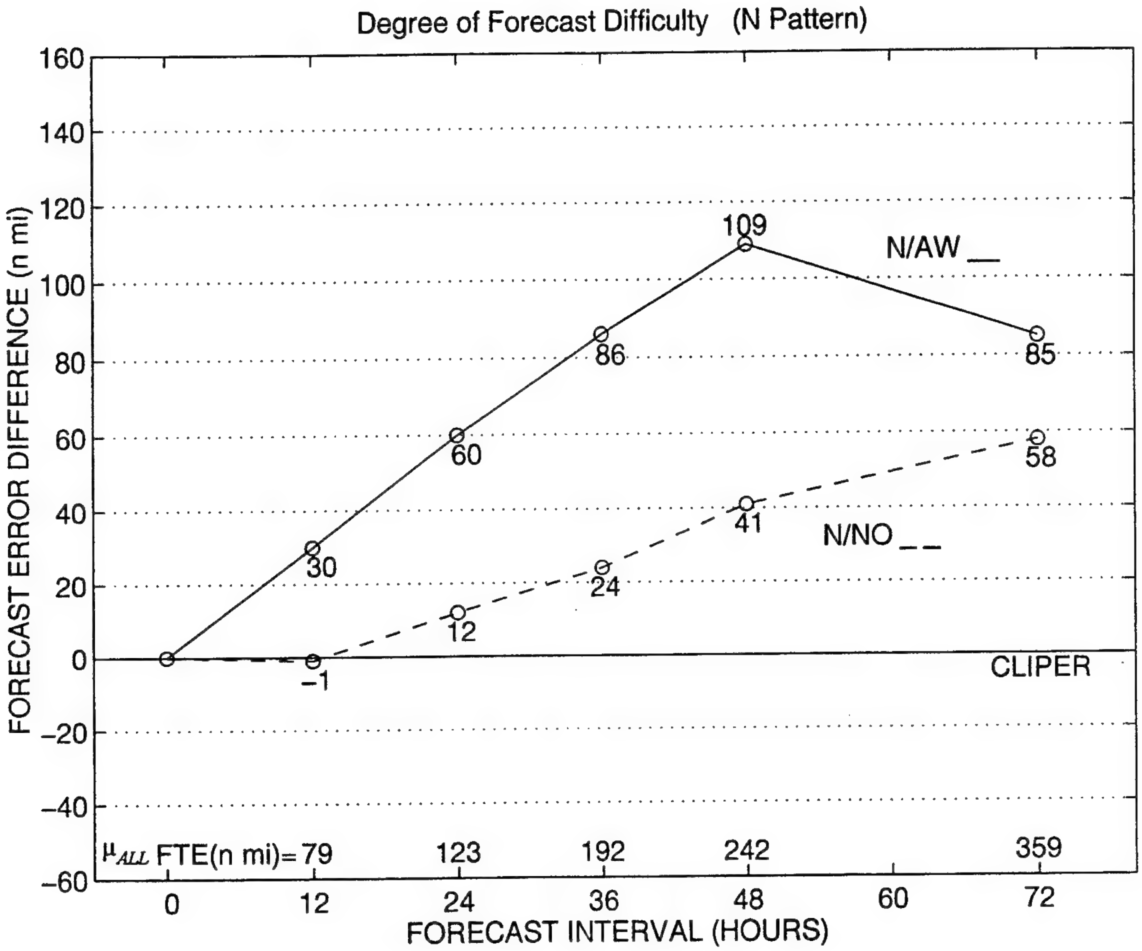

Figure 8 Degree of forecast difficulty as in Fig. 7, except for the North-oriented (N) Pattern. See Table 3 for further details.

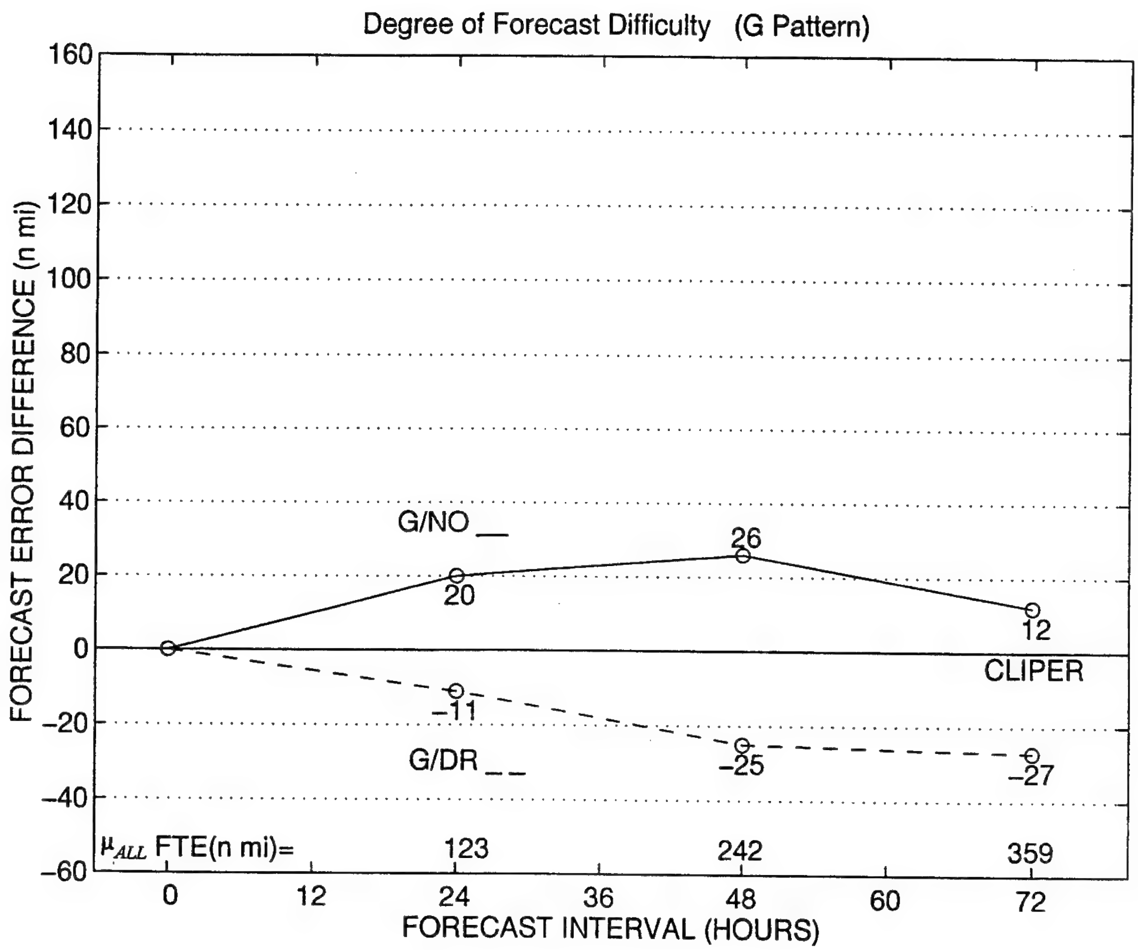

Figure 9 Degree of forecast difficulty as in Fig. 7, except for the Gyre (G) Pattern. See Table 4 for further details.

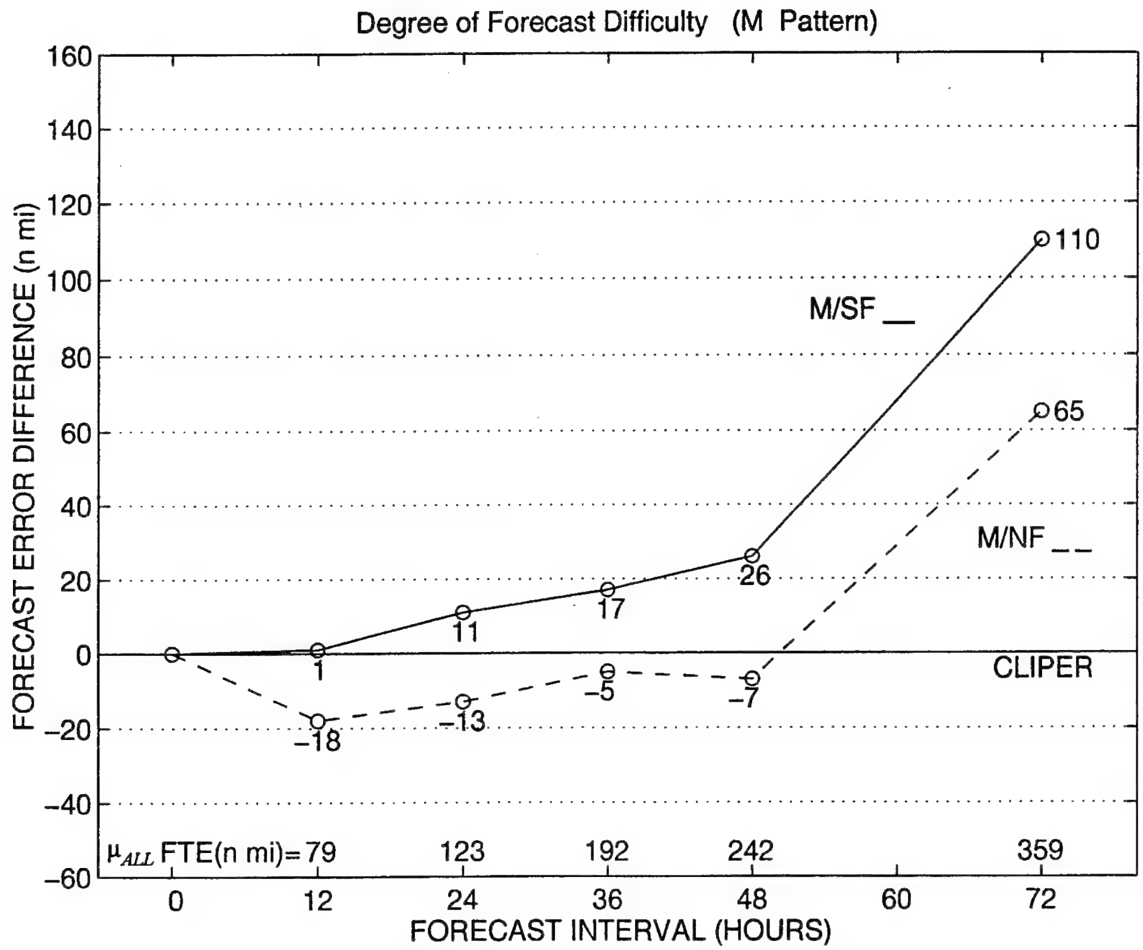

Figure 10 Degree of forecast difficulty as in Fig. 7, except for the Multiple (M) Cyclone Pattern. See Table 5 for further details.

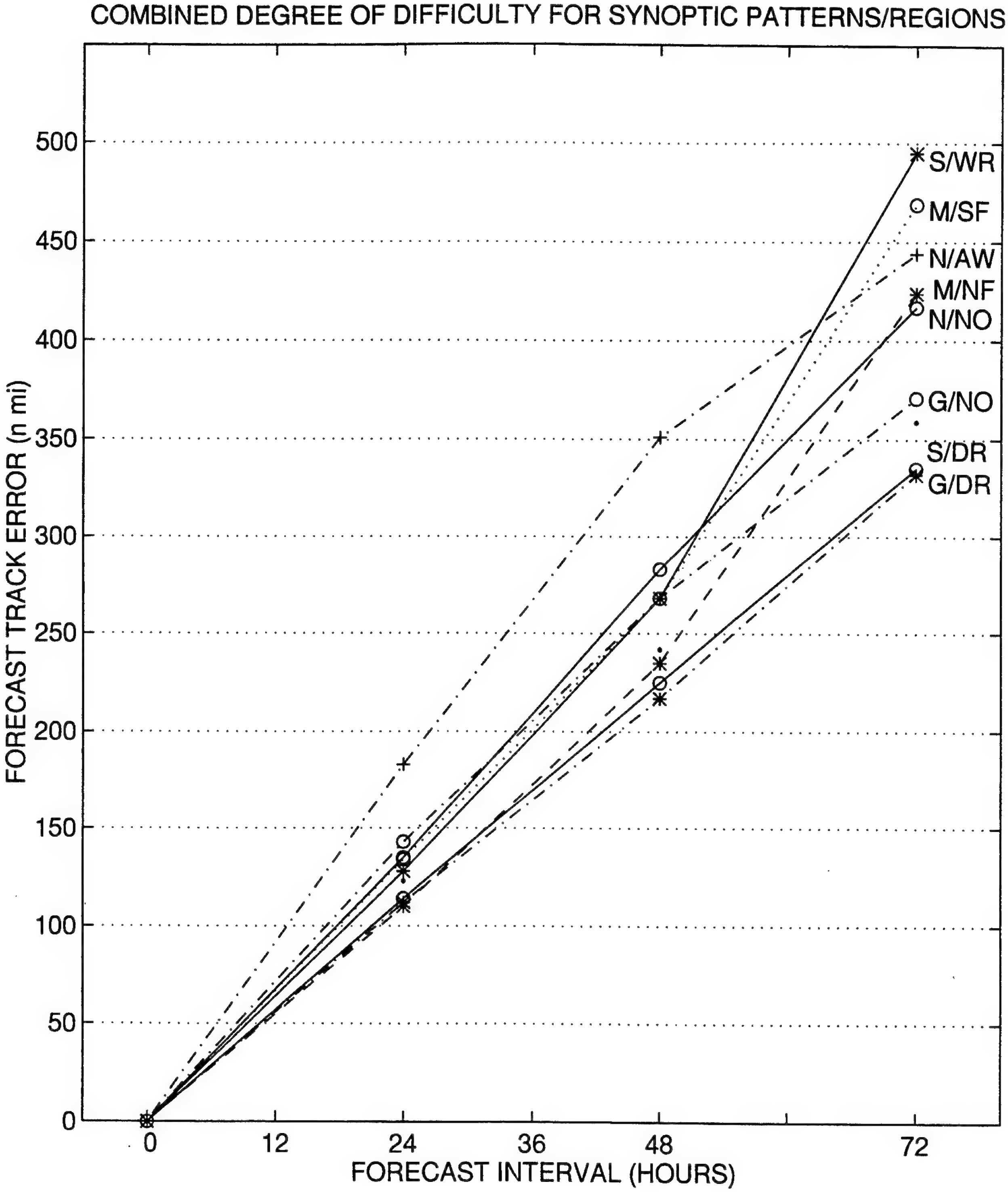

Figure 11 Combined degree of forecast difficulty for eight Pattern/Region combinations; S/AW and G/AW had too few samples. Storms in those Pattern/Region combinations that have larger (smaller) CLIPER FTEs are more (less) difficult to forecast.

IV. SKILL OF JTWC TRACK FORECASTS

As previously discussed, using the CLIPER FTE within the specific Synoptic Pattern/Region combinations is a better measure of the degree of difficulty of the track forecast than the CLIPER FTE for all storms combined. Comparison will now be made between the official JTWC forecasts and CLIPER (P/R) as a measure of skill. Negative (positive) FTE differences indicate the JTWC forecast has skill (no skill) relative to CLIPER FTE, which is the new standard of comparison within the specific Pattern/Region. Once skill or no skill has been identified for JTWC within the Pattern/Region combinations, the degree of confidence in the JTWC forecasts can be evaluated separately for those Patterns/Regions.

Graphs were created for each Synoptic Pattern/Region similar to Figs. 2 through 5, except the comparison is between mean JTWC FTEs and CLIPER (P/R) FTEs at 12, 24, 36, 48, and 72 h. In each comparison, the samples are homogeneous, which ensures a meaningful comparison of forecast scenarios since exactly the same initial times are included.

The statistical method to determine if the mean FTEs are equal (i.e., statistically no difference) or not equal (i.e., statistically different) will be the two sample *t*-test with a confidence level of 95%,

$$t_{(n_1+n_2-2)} = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}\sqrt{\frac{(n_1-1)s_1^2 + (n_2-1)s_2^2}{(n_1+n_2-2)}}} \quad . \tag{2}$$

This statistical analysis takes into account the sample sizes (n_1 and n_2), means ($\bar{x}_1$ and $\bar{x}_2$), standard deviations (s_1 and s_2), and degrees of freedom (n_1+n_2-2) of the FTEs for each

forecast time of each Pattern/Region combination (see Tables 6, 7, 8, and 9 below for the S, N, G, and M Synoptic Patterns, respectively). Since the comparisons will be done with homogeneous sample sizes, n_1 is equal to n_2 for each respective forecast time (12, 24, 36, 48, and 72 h). The statistical test results can be grouped into three categories: skill, no skill, or undetermined. If the statistical test indicates the negative (positive) mean FTE differences between JTWC and CLIPER (P/R) are sufficiently large to be judged statistically not equal at a confidence level of 95% or greater, then JTWC is said to have skill (no skill) in that specific Pattern/Region for that forecast time. If the confidence level is less than 95%, then it can not be concluded that the mean $(FTE_{JTWC} - FTE_{CLIPER})$ difference is different from zero, and the skill level is undetermined for the JTWC forecast. Three reasons for the FTE difference to be labeled as undetermined include: (i) the mean $(FTE_{JTWC} - FTE_{CLIPER})$ difference is indeed small; (ii) the number of cases for the forecast time is too small for a clear decision that the $(FTE_{JTWC} - FTE_{CLIPER})$ difference is not equal to zero; or (iii) the standard deviations of one or both of the aids are too large.

One of the conditions for applying such a statistical test is that each entry in the sample is independent. Clearly, two forecasts separated by only 6 h are not independent as the same meteorological data are being utilized and the forecast scenario has not changed. To approximate the requirement that each sample (i.e., forecast) be independent, the degrees of freedom (DOF) cases is defined to be the number of cases in which the forecasts are separated by 30 h (values are given in Tables 6, 7, 8, and 9). Although the FTE differences are for the entire sample, the DOF case value is the number (n) of samples to be entered in the *t*-test. The actual numerical value for degrees of freedom for the *t*-test is calculated by

adding the two sample DOF cases minus two (i.e., $n_1 + n_2 - 2$). Because this estimate of independent or DOF cases is typically a reduction by a factor of about four, the effect is to reduce the number of Pattern/Region combinations in which it can be statistically demonstrated that the JTWC forecasts have skill compared to CLIPER (P/R). As more JTWC forecasts with the Systematic Approach classification of Synoptic Pattern/Regions become available, even some of the small ($FTE_{JTWC} - FTE_{CLIPER}$) differences will move from the statistically undetermined category to the skill or no skill category.

A. STANDARD SYNOPTIC PATTERN

The mean ($FTE_{JTWC} - FTE_{CLIPER}$) differences for the Standard/Dominant Ridge (S/DR) Synoptic Pattern/Region (Fig. 12--end of this chapter) are relatively small (13, 14, 26, 36, and 52 n mi for the 12, 24, 36, 48, and 72 h forecasts, respectively). However, the DOF cases (213, 443, 186, 382, and 329) are very large (Table 6), even after the reduction of the total number of cases to obtain independent samples. Because even the smallest of these DOF cases is greater than the *t*-test table value for 120 cases, any *t* values that exceed 1.645 for these sample sizes are above the 95% confidence level (Anderson and Sclove 1986). For example, the test values in Table 6 and along the bottom of Fig. 12 may be interpreted that JTWC forecasts within the S/DR Synoptic Pattern/Region have statistically significant skill as compared to CLIPER at all forecast times from 12 h to 72 h.

The 72 h mean ($FTE_{JTWC} - FTE_{CLIPER}$) difference of -178 n mi for the S/WR Pattern/Region is the largest mean FTE difference of any Pattern/Region combination (Fig. 13). Such a large value would normally be expected to be significant, and therefore the JTWC forecasts would have skill at this forecast period. However, there are only 15

Table 6. Statistical summary for estimation of skill, no skill, or undetermined for JTWC forecasts in the S Synoptic Pattern. The *t*-test values (* indicates the *t* value is statistically significant) for each Region of the S Synoptic Pattern are calculated from the two sample, one-tailed *t*-test (Eq. 2) based on the sample mean differences ($\bar{x}_1$ - $\bar{x}_2$)=($\bar{x}_{DIFF}$) and standard deviations (s_1 and s_2) of the forecast track errors (FTEs in n mi) of JTWC and CLIPER (P/R), and the number of independent samples ($n_{DOF\ cases}$). The $n_{DOF\ cases}$ is the sample size used for both n_1 and n_2 in Eq. (2), since the comparisons are for homogeneous samples.

		Forecast Period				
		12 h	**24 h**	**36 h**	**48 h**	**72 h**
S/DR						
	t-test	-3.042*	-3.196*	-2.637*	-4.004*	-3.715*
	skill level	skill	skill	skill	skill	skill
	$\bar{x}_{DIFF}$	-13	-14	-26	-36	-52
	s_{JTWC}	41	60	91	116	176
	s_{CLIPER}	47	70	99	132	183
	n_1, n_2	854	1847	766	1591	1353
	$n_{DOF\ cases}$	213	443	186	382	329
S/WR						
	t-test	-0.587	-1.266	-1.167	-1.442	-1.685
	skill level	undet	undet	undet	undet	undet
	$\bar{x}_{DIFF}$	-10	-21	-61	-62	-178
	s_{JTWC}	43	73	100	131	196
	s_{CLIPER}	47	84	168	191	359
	n_1, n_2	46	144	36	86	44
	$n_{DOF\ cases}$	14	45	14	29	15

independent cases at 72 h in this sample of five years. This case dramatically demonstrates how the degrees of freedom can have a major impact on the two-sample *t*-test. Only if more cases with roughly the same mean FTE are included would it be statistically demonstrated that the JTWC 72 h forecasts in the S/WR Pattern/Region have skill over CLIPER (Table 6). Although the degrees of freedom cases are tripled or doubled at 24 h and 48 h, the (JTWC - CLIPER) FTE differences are much smaller than at 72 h (Fig. 13). Thus, the JTWC forecasts in the WR Region in the S Pattern are judged to be in the undetermined skill category since all of the *t* values are below the 95% confidence level.

There were too few cases (less than 10) in the S/AW Pattern/Region, so that Pattern/Region will not be discussed.

B. NORTH-ORIENTED SYNOPTIC PATTERN

The JTWC forecasts in the N/NO Synoptic Pattern/Region (Fig. 14) have relatively small improvements over CLIPER at all times. However, the DOF cases are rather large for the 24 h and 48 h forecasts. Given also the larger standard deviations of the FTEs with increasing forecast intervals, the N/NO *t*-test values are above the 95% confidence level *t* value of 1.645 for all forecast periods except 72 h (Table 7). It is thus demonstrated at this confidence level that the 12 h through 48 h JTWC forecasts in the N/NO Pattern/Region have skill compared to CLIPER. However, the 72 h JTWC forecasts have an undetermined skill due to the low *t*-test value. That is, the number of independent cases (100) at this forecast

Table 7. Statistical summary for estimation of skill of JTWC forecasts as in Table 6, except for the N Synoptic Pattern.

		Forecast Period				
		12 h	**24 h**	**36 h**	**48 h**	**72 h**
N/NO						
	t-test	-2.021*	-2.133*	-2.155*	-2.092*	-1.235
	skill level	skill	skill	skill	skill	undet
	$\bar{x}_{DIFF}$	-16	-18	-45	-41	-40
	s_{JTWC}	44	74	109	148	222
	s_{CLIPER}	52	84	130	172	236
	n_1, n_2	292	673	254	513	346
	$n_{DOF\ cases}$	74	176	66	134	100
N/AW						
	t-test	0.520	1.309	0.296	1.026	0.849
	skill level	undet	undet	undet	undet	undet
	$\bar{x}_{DIFF}$	-12	-31	-33	-86	-73
	s_{JTWC}	80	95	204	215	94
	s_{CLIPER}	73	103	182	195	144
	n_1, n_2	52	103	14	32	16
	$n_{DOF\ cases}$	22	35	6	12	4

period is too small to demonstrate that the ($FTE_{JTWC} - FTE_{CLIPER}$) difference of 40 n mi is statistically significant.

The JTWC FTEs in the N/AW Pattern/Region (Fig. 15) are smaller than CLIPER FTEs. An improvement of 86 n mi at 48 h would normally be considered to be a demonstration of skill. However, the statistical analysis indicates that the JTWC FTEs at all forecast periods have *t*-test values that are less than the 95% confidence level (Table 7). Clearly, the inability to demonstrate statistically the JTWC skill arises from the small number of independent cases. Although 32 cases are available at 48 h, only 12 are considered to be independent. This is too small of a sample to demonstrate confidently that the 86 n mi improvement relative to CLIPER represents skill. The 24 h JTWC forecast improvement of 31 n mi is based on 103 cases, of which 35 are separated by at least 30 h. This is not enough independent cases to demonstrate skill. Although the JTWC forecasts in the N/AW Pattern/Region must be classified as having undetermined skill, this conclusion may change when more independent cases are included.

C. GYRE SYNOPTIC PATTERN

The mean JTWC FTE at 24 h for storms in the AW Region of the Gyre (G) Synoptic Pattern is 78 n mi better than the CLIPER FTE (Fig. 16). This is the largest 24 h FTE improvement in all of the Pattern/Region combinations. Because this FTE improvement is so large, these JTWC forecasts may be considered to have skill according to the *t*-test. However, the number of independent cases is only four, and therefore this must be considered to be an unreliable sample.

Table 8. Statistical summary for estimation of skill of JTWC forecasts as in Table 6, except for the G Synoptic Pattern.

		Forecast Period				
		12 h	**24 h**	**36 h**	**48 h**	**72 h**
G/NO						
	t-test	-1.171	-0.636	-0.956	-0.676	+0.364
	skill level	undet	undet	undet	undet	undet
	$\bar{x}_{DIFF}$	-22	-10	-43	-20	+15
	s_{JTWC}	49	75	107	126	161
	s_{CLIPER}	57	96	130	159	188
	n_1, n_2	62	219	50	168	127
	$n_{DOF\ cases}$	16	60	14	47	36
G/DR						
	t-test	N/A	-0.337	N/A	-1.116	-1.259
	skill level		undet		undet	undet
	$\bar{x}_{DIFF}$		-6		-35	-62
	s_{JTWC}		65		108	177
	s_{CLIPER}		77		122	164
	n_1, n_2	0	116	0	102	91
	$n_{DOF\ cases}$	0	32	0	27	24

The JTWC FTEs in the G/NO Pattern/Region combination (Fig. 17) are somewhat small improvements relative to CLIPER at 12 h through 48 h, and are actually degraded relative to CLIPER at 72 h. This is only one of two instances in which the mean JTWC FTE difference is positive relative to the CLIPER (P/R) FTE; the other Pattern/Region in which this is true is the M/NF combination, which will be discussed later. The larger improvements at 12 h and 36 h are for fewer DOF cases at (16 and 14, respectively) as compared with the 24, 48, and 72 h forecasts (60, 47, and 36, respectively). The skill level for all JTWC forecasts in the G/NO combination is thus considered to be undetermined at all forecast intervals (Table 8).

The JTWC forecasts in the G/DR Synoptic Pattern/Region combination are almost equal to the CLIPER FTEs at 24 h and then are improved by 35 n mi and 62 n mi at 48 h and

72 h, respectively (Fig. 18). Recall that no 12 h or 36 h forecasts are available in this Pattern/Region. Again, the sample sizes are small, with only 27 and 24 independent cases at 48 h and 72 h, respectively. Consequently, the conclusion is that the JTWC forecasts in the G/DR combination have undetermined skill as indicated by the *t*-test (Table 8). When more data are available, it is anticipated that this Pattern/Region will indicate skill for the JTWC forecasts based on these negative mean $(FTE_{JTWC} - FTE_{CLIPER})$ differences.

D. MULTIPLE CYCLONE SYNOPTIC PATTERN

The JTWC forecasts in the SF Region of the Multiple (M) Tropical Cyclone Synoptic Pattern (Fig. 19) are generally close to the CLIPER FTEs at 12 through 36 h, and then are improved by 40 n mi and 75 n mi at 48 h and 72 h, respectively. Although the 72 h improvement would normally be thought to be significant, it is based on only 10 independent cases. Thus, the conclusion of skill at 72 h can not be justified with a 95% level of confidence based only on this sample size (Table 9). However, larger sample sizes may change this determination.

Based on very small $(FTE_{JTWC} - FTE_{CLIPER})$ differences for the NF Region of the M Pattern (Fig. 20), the JTWC forecasts do not have skill compared with CLIPER (Table 9). The 72 h forecast is the second instance in which the mean FTE difference of JTWC is actually positive relative to CLIPER (P/R). However, the statistical test indicates that this is not a significant difference (i.e., the mean FTEs of JTWC and CLIPER (P/R) are considered to be equal). Therefore, the conclusion is that the JTWC forecasts in the NF Region of the M Pattern have undetermined skill for all five forecast intervals.

Table 9. Statistical summary for estimation of skill of JTWC forecasts as in Table 6, except for the M Synoptic Pattern.

		Forecast Period				
		12 h	**24 h**	**36 h**	**48 h**	**72 h**
M/SF						
	t-test	-0.633	-0.710	-0.093	-0.653	-0.643
	skill level	undet	undet	undet	undet	undet
	$\bar{x}_{DIFF}$	-14	-19	-5	-40	-75
	s_{JTWC}	40	70	81	120	194
	s_{CLIPER}	53	81	117	175	314
	n_1, n_2	34	62	27	46	35
	$n_{DOF\ cases}$	9	16	7	12	10
M/NF						
	t-test	-0.241	-0.234	-0.014	-0.073	+0.076
	skill level	undet	undet	undet	undet	undet
	$\bar{x}_{DIFF}$	-4	-5	-1	-4	+8
	s_{JTWC}	31	63	136	158	290
	s_{CLIPER}	31	65	137	154	289
	n_1, n_2	33	77	31	69	64
	$n_{DOF\ cases}$	7	18	7	16	15

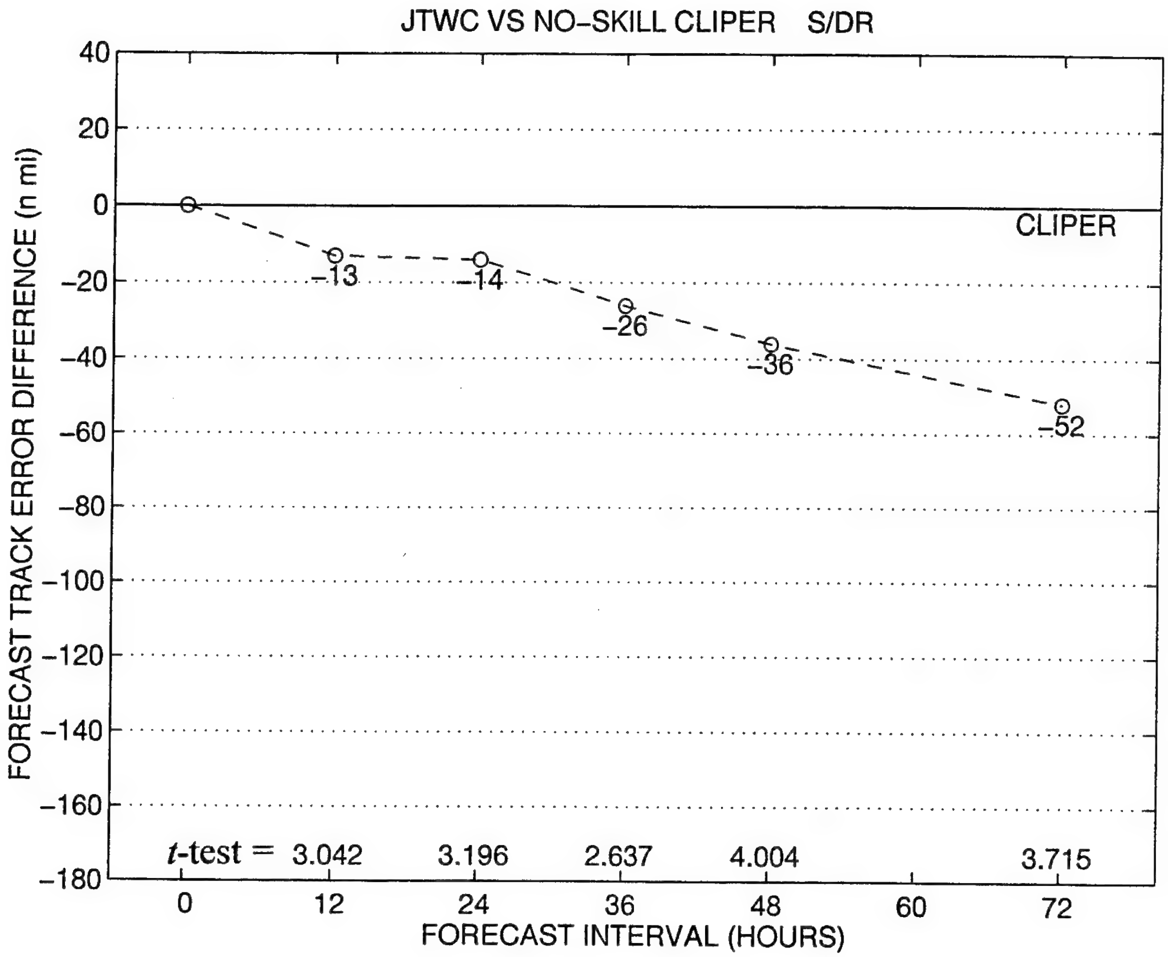

Figure 12 Evaluation of skill of JTWC forecasts as compared to the no-skill CLIPER forecasts for the Dominant Ridge (DR) Region of the S Pattern. The two sample *t*-test results are indicated along the bottom axis for each forecast period. The JTWC and CLIPER mean differences ($\bar{x}_{DIFF}$) are the numerical values near each point of the graph. See Table 6 for further details.

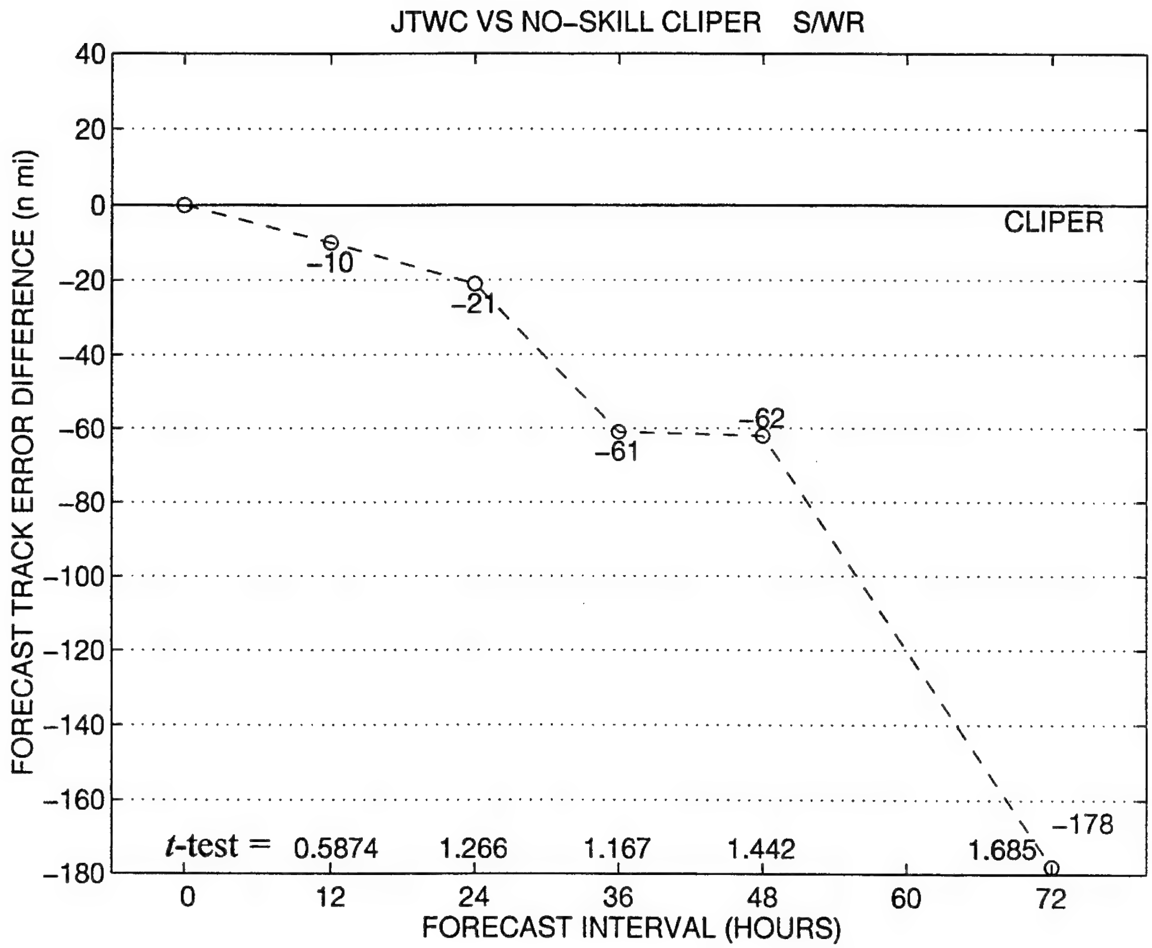

Figure 13 Evaluation of skill of JTWC forecasts as in Figure 12, except for the Weakened Ridge (WR) Region of the S Pattern. See Table 6 for further details.

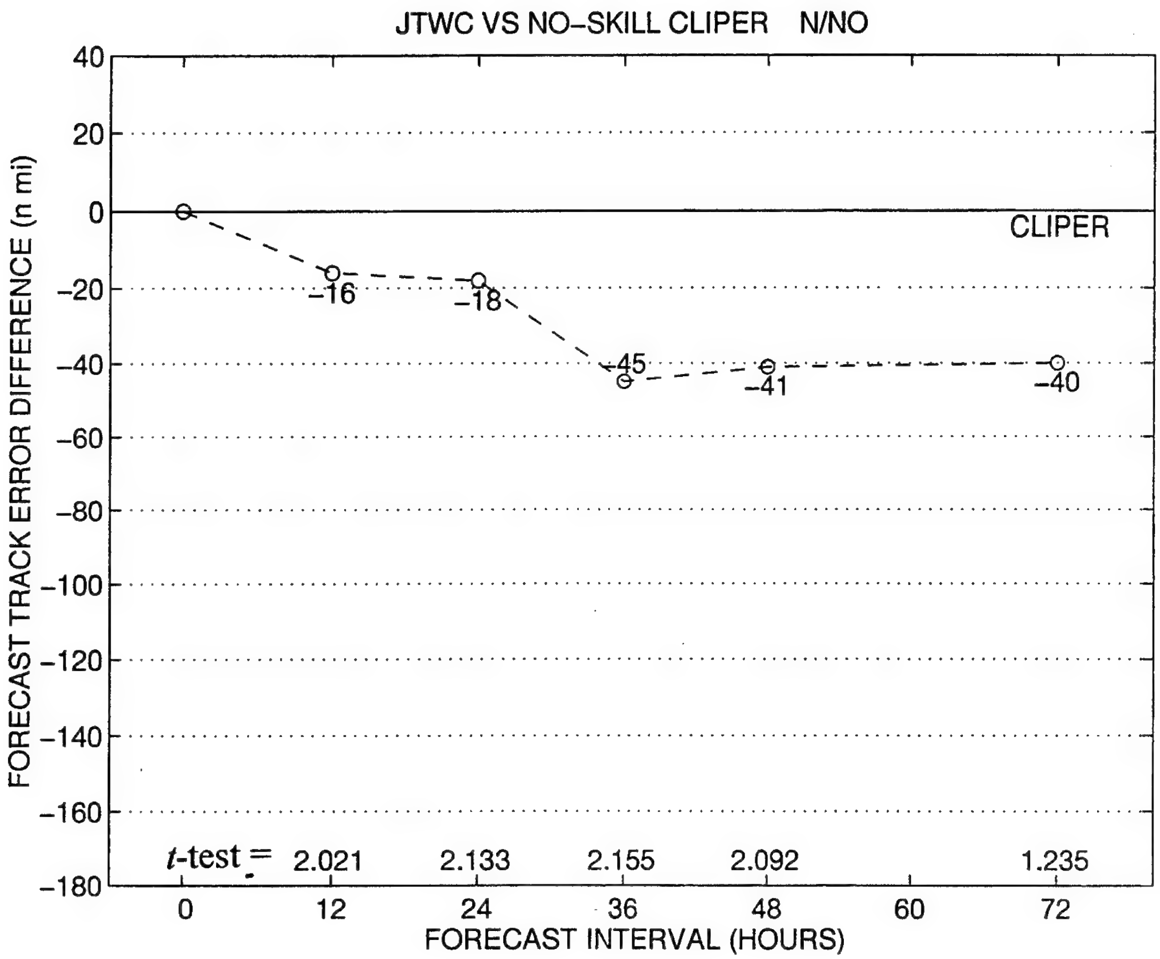

Figure 14 Evaluation of skill of JTWC forecasts as in Figure 12, except for the North-Oriented (NO) Region of the N Pattern. See Table 7 for further details.

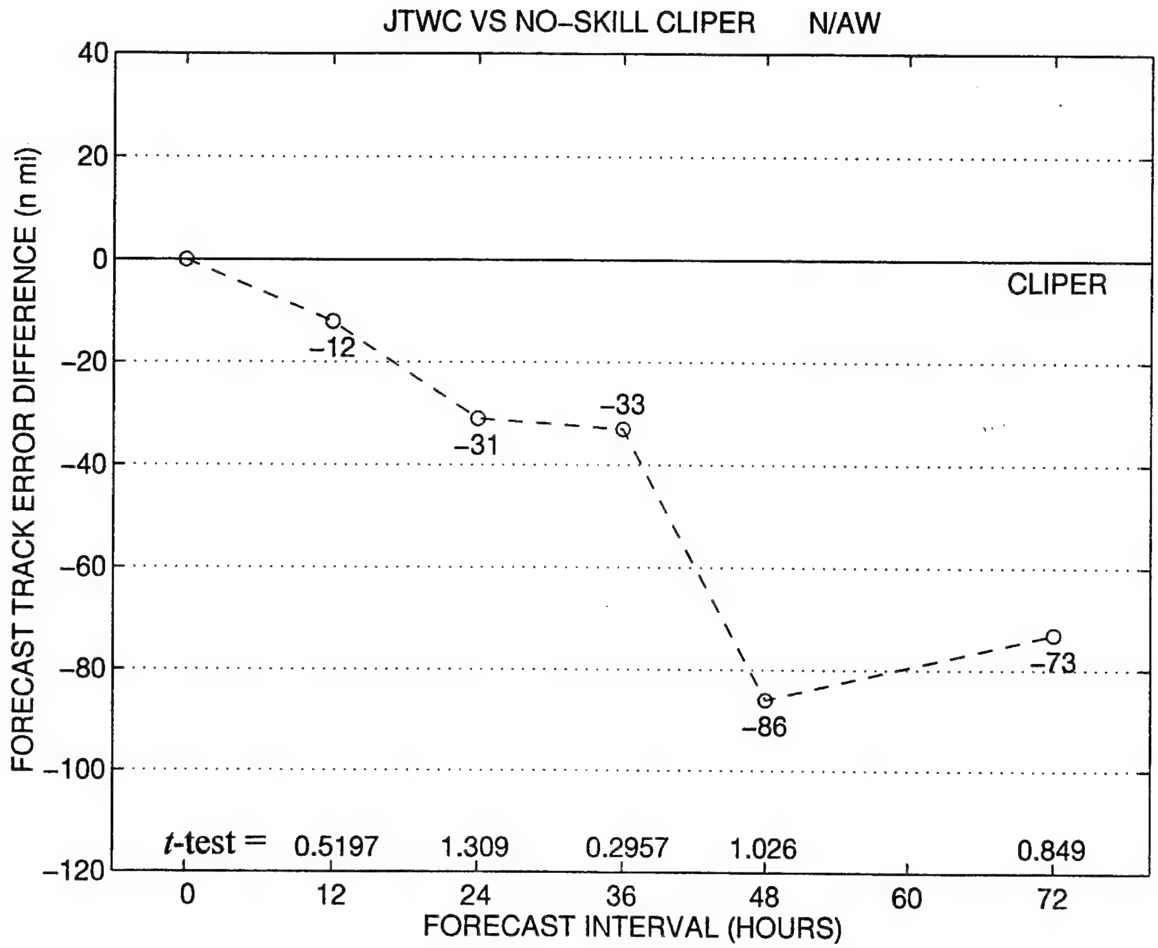

Figure 15 Evaluation of skill of JTWC forecasts as in Figure 12, except for the Accelerating Westerlies (AW) Region of the N Pattern. See Table 7 for further details.

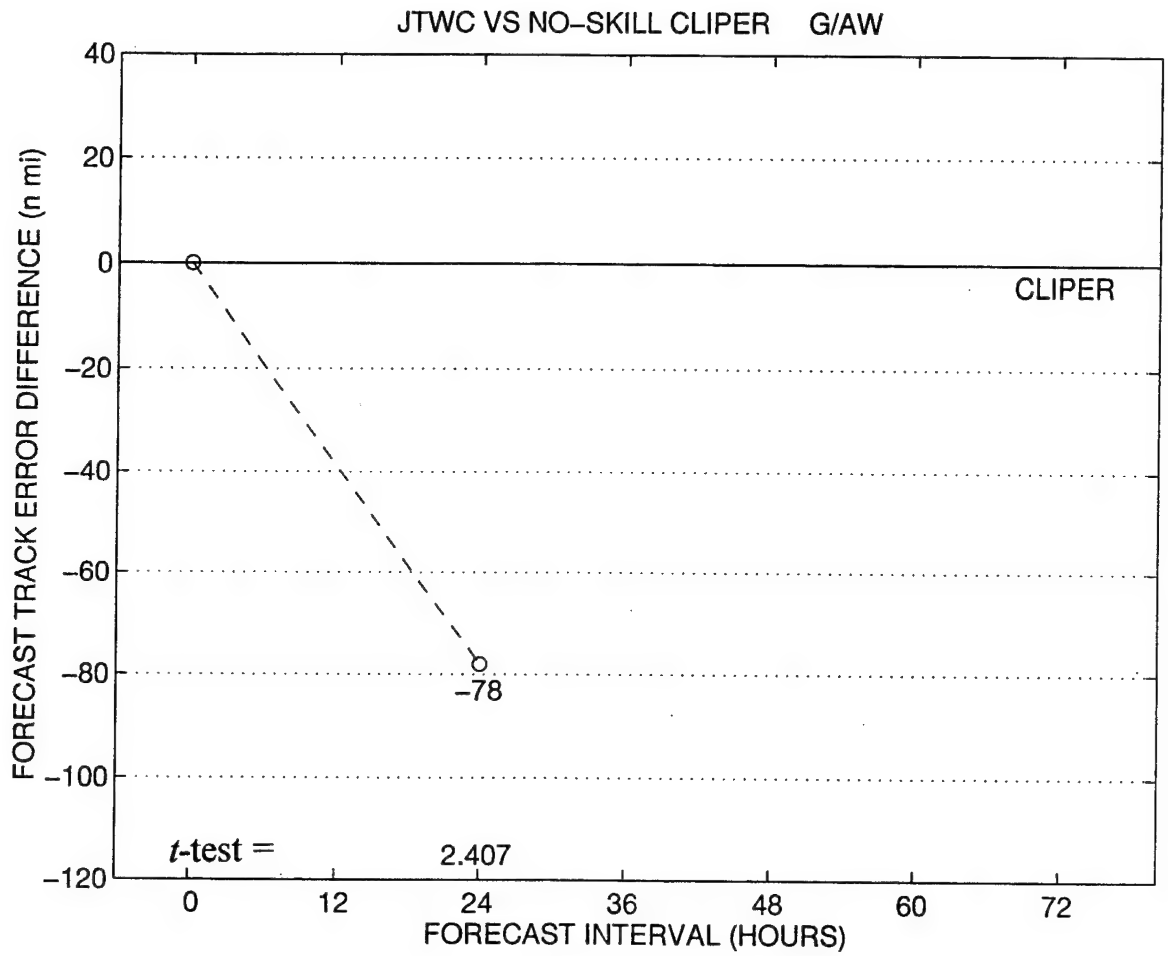

Figure 16 Evaluation of skill of JTWC forecasts as in Figure 12, except for the Accelerating Westerlies (AW) Region of the G Pattern.

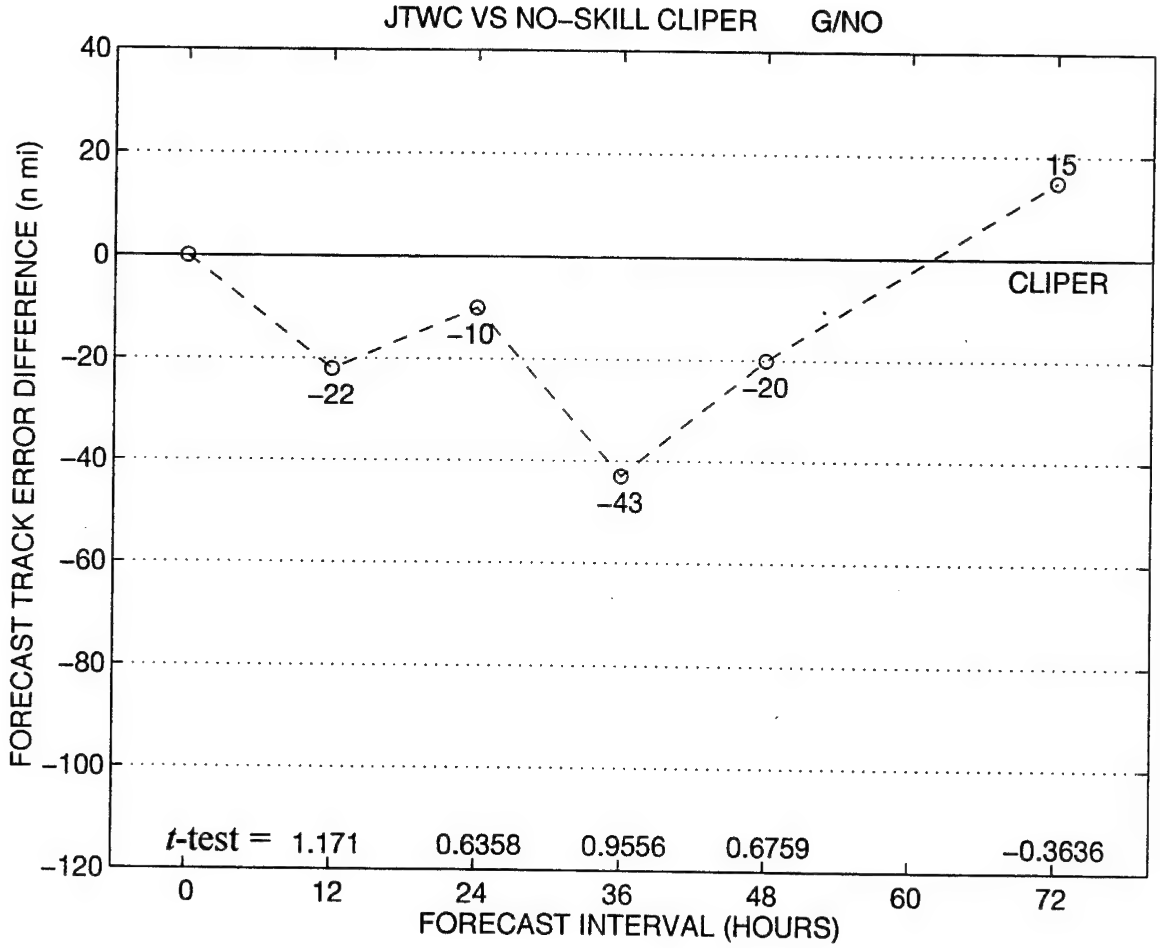

Figure 17 Evaluation of skill of JTWC forecasts as in Figure 12, except for the NO Region of the G Pattern. See Table 8 for further details.

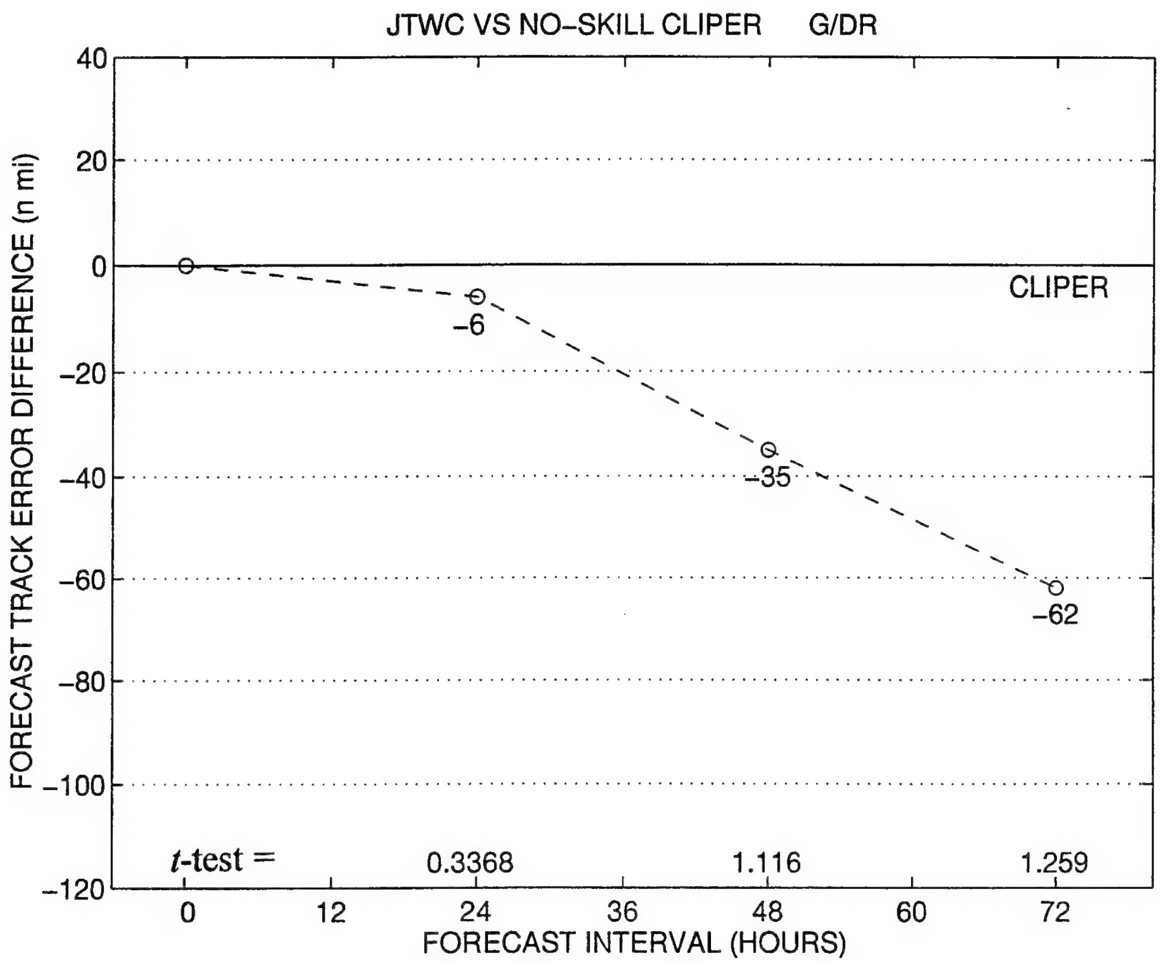

Figure 18 Evaluation of skill of JTWC forecasts as in Figure 12, except for the DR Region of the G Pattern. See Table 8 for further details.

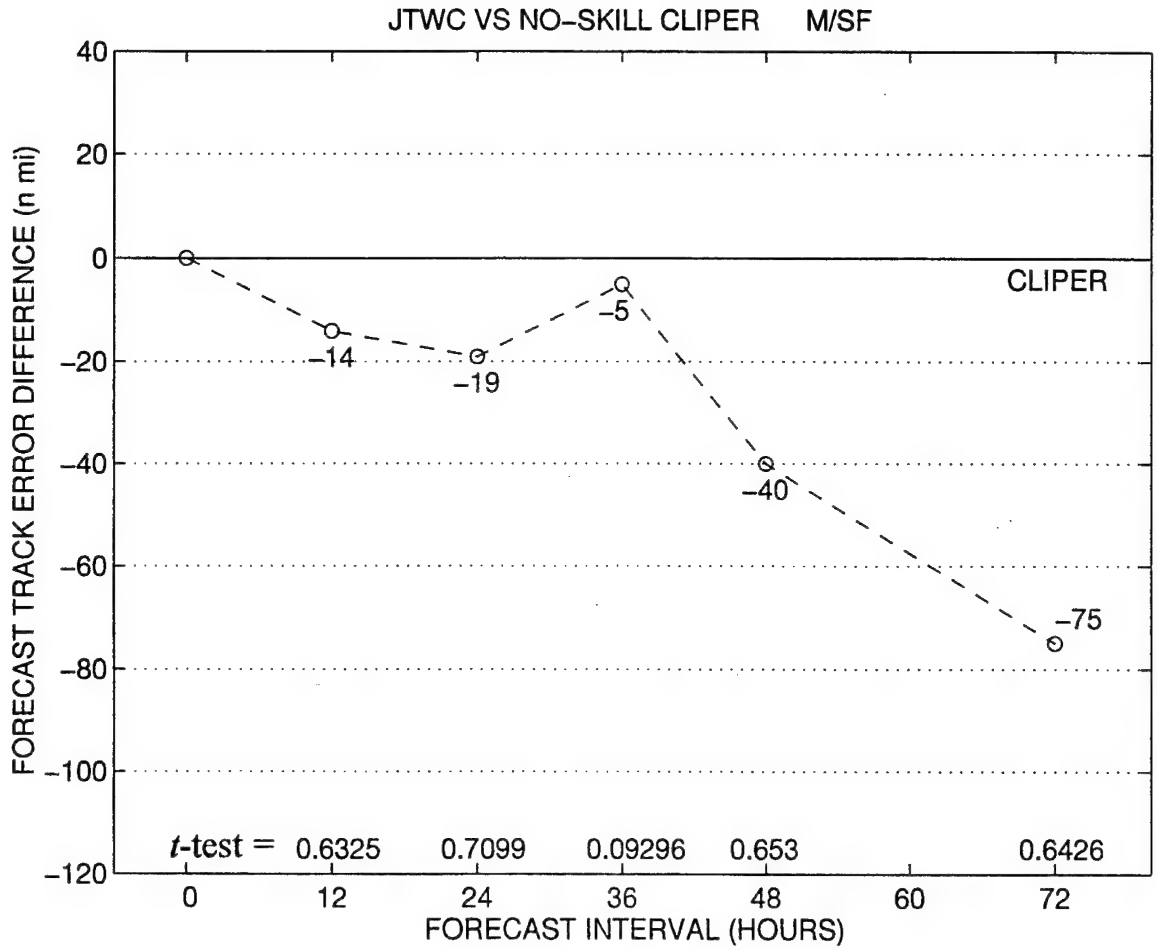

Figure 19 Evaluation of skill of JTWC forecasts as in Figure 12, except for the Southerly Flow (SF) Region of the M Pattern. See Table 9 for further details.

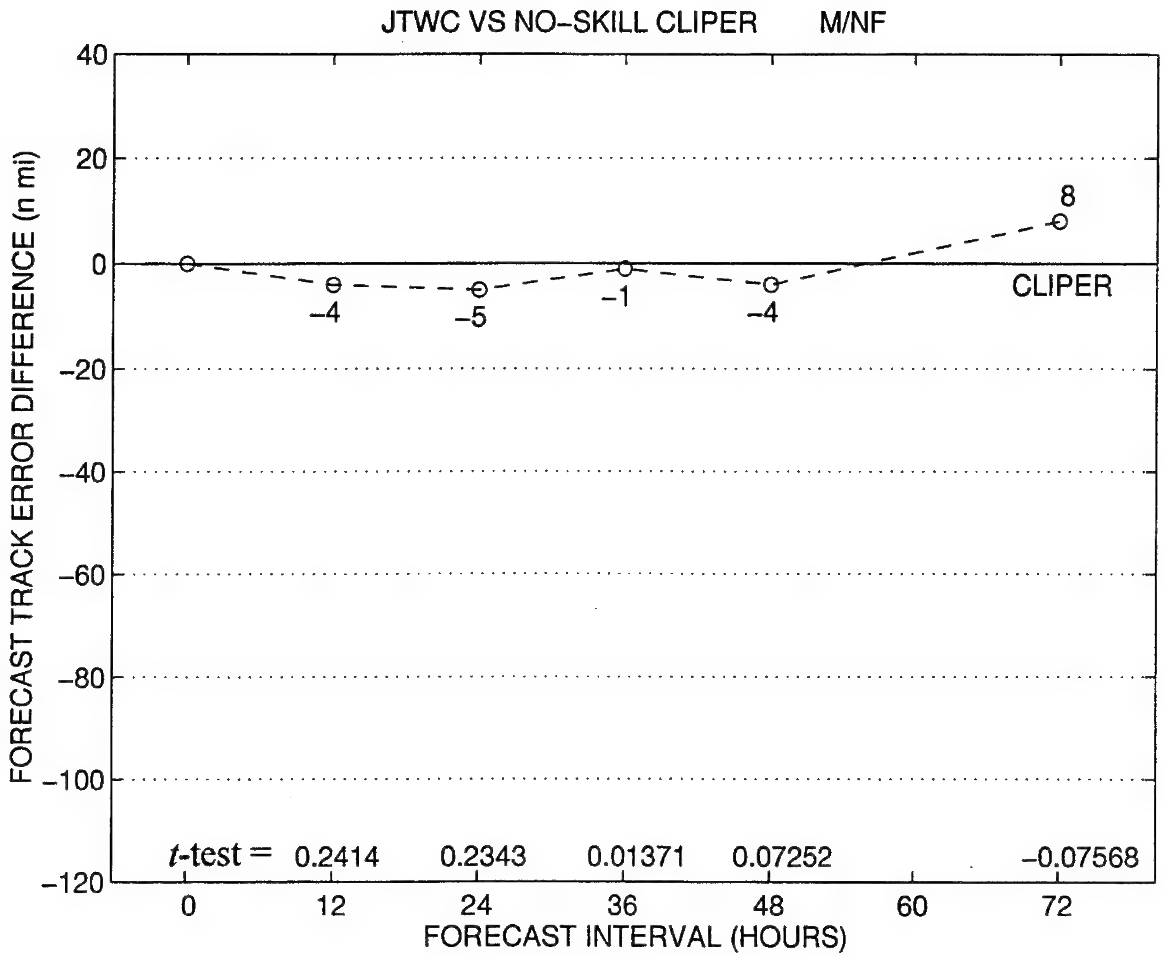

Figure 20 Evaluation of skill of JTWC forecasts as in Figure 12, except for the Northerly Flow (NF) Region of the M Pattern. See Table 9 for further details.

V. TRANSITIONS

Tracks of storms that remain in a particular Pattern/Region (Figs. 2 through 5) are expected to have persistent paths until an Environmental Structure transition occurs. Thus, another challenge for the forecaster is to recognize when the Environmental Structure will change, which is then expected to lead to a significant track deviation from a persistence forecast (e.g., differences between tracks in Figs. 2 - 5). Since such track changes (and non-climatological situations) are hypothesized to be more difficult, the degree of difficulty should increase during transitions. As in Chapter III, the degree of difficulty is described in terms of the CLIPER FTEs.

Since only 43 of the 166 storms in the five-year data base remained within just one Pattern/Region for their entire existence, the remaining 123 storms went through one or more transitions (see Carr *et al.* 1995 for further details). The total number of transitions was 248, which emphasizes the need to evaluate the track forecast performance of JTWC "before" and "after" the actual transition time to determine any systematic error tendencies. Only "complete" transitions are included to exclude those periods of dual Synoptic Pattern/Region assignments in which it appears a transition is approaching, but an actual change of either the Region, or the Pattern, or both, has not occurred.

Homogeneous comparisons of CLIPER and JTWC track forecast errors relative to transition time are shown in Figs. 21 through 24 (at end of this chapter) for the four most frequently recurring transitions found by Carr *et al.* (1995; their Fig 2.9). As explained in Chapter II, the mean FTEs were calculated for JTWC and CLIPER for forecast periods 24, 48, and 72 h for 12 h increments from 72 h before the transition to 48 h after the transition.

Because the 12 h and 36 h forecasts were not produced before 1992, the number of cases for these forecasts were generally too few (less than 10) to be considered reliable, and thus the 12 h and 36 h forecasts will not be included. Statistical analysis was done using the two-sample t-test (Eq. 2) with a confidence level of 95% and $(n_1 + n_2 - 2)$ degrees of freedom, where n_1 equals n_2 since the sample is homogeneous at each time prior and subsequent to the transition. As explained in Chapter II, the sample size decreases with time away from the transition time. No reduction in sample size to account for the degrees of freedom is necessary here as each transition is usually for a unique TC, or in the relatively few cases in which a TC undergoes a particular transition, two or more (very rare), the time interval is sufficient to ensure statistical independence.

A. S/DR TO N/NO TRANSITIONS

Storms that begin in S/DR and transition to the N/NO Pattern/Region will generally have a westward track (Fig. 2a) and eventually become northward as in Fig. 3a after the time of transition, which is depicted by the solid vertical at 0 h (Fig. 21). The number of cases for the three forecast periods (24, 48, and 72 h) ranges from 37 to 9 with the smallest sample sizes for the 72 h forecasts at transition time plus 48 h. Compared to the case numbers of the homogeneous samples in the two Pattern/Regions (Figs. 12 and 14) involved in this transition, these sample sizes are dramatically smaller. The relatively small sample sizes will have an important impact on the statistical significance tests (see Tables 10, 11, 12, and 13 below) since the sample size is important in the calculation of the t-test value.

The overall trend for the mean CLIPER errors in the transition from the S/DR to the N/NO Pattern/Region (Fig. 21) is smaller FTEs at -72 h before transition time, gradual

increases in FTEs toward transition time, and then a FTE decrease after the transition to N/NO, although not to values as small as in the SDR Pattern/Region before the transition. Notice that the CLIPER FTE values approaching the transition are increasingly larger from 24 h to 48 h to 72 h. These FTE trends are interpreted to mean that the forecast degree of difficulty is a maximum at transition time, and is progressively more difficult at 48 h and 72 h. This is reasonable because a missed forecast of the westward-to-northward track change during this transition would lead to larger and larger errors with increasing forecast interval.

Table 10. Statistical summary for comparison of JTWC and CLIPER FTEs in n mi from 72 h before to 48 h after the transition from the S/DR to the N/NO Synoptic Pattern/Region. Since the sample is homogeneous n_1 and n_2 for the one-sided, two sample t-test (Eq. 2) are the same, and $\bar{x}$ and s refer to the sample means and standard deviations of the FTEs. Shaded boxes in the t-test column indicate statistical significance at the 95% confidence level.

Time rel to trans	**24 h forecasts**						**48 h forecasts**						**72 h forecasts**					
		CLIPER			JTWC			CLIPER			JTWC			CLIPER			JTWC	
	t-test	$\bar{x}$	s	$n_{1,2}$	$\bar{x}$	s	t-test	$\bar{x}$	s	$n_{1,2}$	$\bar{x}$	s	t-test	$\bar{x}$	s	$n_{1,2}$	$\bar{x}$	s
-72	*-1.757*	163	144	18	99	56	-1.502	227	150	18	167	79	-0.848	277	151	18	240	107
-60	-0.087	85	32	23	84	45	-0.529	164	76	23	151	90	+0.025	255	129	23	256	147
-48	-0.276	100	59	28	96	49	-0.237	202	134	28	194	118	+0.563	320	188	26	348	170
-36	-0.918	105	62	32	91	60	-0.078	203	109	31	201	92	+0.358	355	147	29	370	171
-24	-0.983	134	78	43	116	73	0	253	120	33	253	105	+0.876	405	198	29	446	156
-12	+0.067	125	65	37	126	64	-0.150	274	120	33	269	150	0	436	173	26	436	250
+00	-0.936	157	100	37	137	83	-0.504	319	242	30	291	185	-0.431	459	280	23	423	287
+12	-0.587	117	76	37	108	54	+0.530	214	101	31	229	121	-0.521	317	183	20	286	193
+24	-1.061	111	76	33	93	61	*-1.788*	260	147	25	195	107	-1.398	390	270	15	278	153
+36	-1.059	103	47	26	87	61	*-2.006*	259	115	18	186	103	-0.181	343	158	11	332	126
+48	-1.459	135	71	19	103	64	-1.121	248	124	12	195	107	-0.744	385	124	9	331	179

Although the 24 h JTWC FTEs are generally slightly lower than the CLIPER FTEs, only at -72 h before transition is the difference between mean JTWC and CLIPER FTEs statistically significant (i.e., CLIPER FTE is greater than JTWC FTE) (see values in Table 10). Thus, the JTWC forecasts generally have undetermined skill compared with CLIPER for the 24 h forecasts prior to and following the S/DR to N/NO transition. A similar result is found for the 48 h forecasts, since only two (+24 h and +36 h) of 11 time segments have statistically significant differences (Table 10). This may be interpreted that the 48 h JTWC forecasts do not have significant skill prior to and within 12 h following the track change to a northward track in the N/NO Pattern/Region (Fig. 3a). Once the track change is completed, then the JTWC forecaster more rapidly adjusts to the new situation than does the CLIPER technique, which depends on the -12 h and -24 h positions. In addition, the low-latitude recurvature associated with the S/DR to N/NO transition is not consistent with climatology, so the CLIPER technique does not perform well. A similar trend is found for the 72 h forecasts (Fig. 21), except that JTWC actually has larger mean FTEs than does the CLIPER technique from -60 h to -12 h before transition time. The JTWC FTEs are lower than for CLIPER just before the transition and remain slightly lower afterward. However, the *t*-test values (Table 10) indicate that the 72 h JTWC forecasts have undetermined skill for all time segments relative to the S/DR to N/NO transition.

B. S/DR TO S/WR TRANSITIONS

The storms that transition from the S/DR to the S/WR Pattern/Region also have dramatic track differences from westward (Fig. 2a) to slow northward (Fig. 2b) motion. The sample size is 32 at transition time, but the numbers of cases quickly decrease after transition

time. The normal recurvature scenario for these storms after the transition from S/DR to S/WR is to then transition to the S/AW (Fig. 2c). Since very few of these recurving storms last more than 36 h in the S/AW Pattern/Region, less than 10 cases are available at +48 h in Fig. 22. Another alternative for storms in the S/WR Pattern/Region is to transition back to S/DR and return to westward motion in a "stair-step track."

Because the differences in tracks following the S/DR to S/WR transition are so large, the degree of difficulty of track forecasts during this transition is expected to be high. This increase in difficulty is indicated by the 48 h and 72 h CLIPER FTE trends in Fig. 22. That is, the mean CLIPER FTEs are increasing while the storm is in the S/DR Pattern/Region from -72 h until the transition, and then decrease while the storm is in the S/WR Pattern/Region. Since the Environmental Structure changes more dramatically for the S/DR to N/NO transition (see Carr and Elsberry 1994) discussed above, the environmental steering is not as well defined or consistent as compared to a typical S/DR Pattern/Region combination. The typical recurvature through the WR Region that is associated with the passage of midlatitude ridges or troughs is clearly more difficult to forecast than the straight-movers in the S/DR Pattern/Region. However, these smaller 24 h CLIPER FTEs for the S/DR to S/WR changes suggest it is easier to forecast this transition than it is to forecast when the building of a North-oriented ridge in the N/NO Pattern/Region combination will lead to the S/DR to N/NO transition (Fig. 21). However, the mean CLIPER FTEs for the 72 h forecasts (Fig. 22) increase dramatically as the S/DR to S/WR transition time approaches, and especially at +12 h and +24 h after the transition when the CLIPER FTE increases to 563 and 611 n mi, respectively (Table 11). The small number of cases (8 and 2 for +12 h and +24 h,

Table 11. Statistical summary for comparison of JTWC and CLIPER as in Table 10, except for the transition from the S/DR to the S/WR Synoptic Pattern/Region.

Time rel to trans	24 h forecasts						48 h forecasts						72 h forecasts					
		CLIPER			JTWC			CLIPER			JTWC			CLIPER			JTWC	
	t-test	$\bar{x}$	s	$n_{1,2}$	$\bar{x}$	s	t-test	$\bar{x}$	s	$n_{1,2}$	$\bar{x}$	s	t-test	$\bar{x}$	s	$n_{1,2}$	$\bar{x}$	s
-72	-0.594	98	58	20	88	48	-0.786	156	101	19	135	58	-1.549	250	98	19	202	93
-60	-0.564	105	68	25	94	70	-1.632	173	92	23	136	58	-1.209	253	122	22	213	96
-48	-1.460	82	39	26	67	35	***-1.762***	172	76	26	137	67	-0.039	290	159	25	288	199
-36	-1.019	93	50	27	79	51	-0.297	186	136	25	175	126	+0.252	327	204	22	343	217
-24	-0.188	95	56	28	92	63	-0.394	243	133	26	227	159	-0.685	365	224	18	314	223
-12	-1.518	124	60	30	102	52	-0.517	290	163	26	268	143	-0.980	411	285	16	326	198
+00	-0.051	123	74	32	122	84	-0.947	289	177	21	244	127	-0.941	484	320	12	378	223
+12	***-2.022***	130	75	19	91	38	***-1.828***	297	219	13	179	79	-1.312	563	428	8	340	219
+24	-0.809	117	93	11	90	60	-0.162	266	274	6	244	189	-0.892	611	660	2	194	44
+36	-0.979	91	60	7	66	31	-0.570	189	57	4	169	41	N/A	335	0	1	336	0

respectively) prohibits any valid statistical analysis, but these large CLIPER FTEs indicate further study is prudent.

Although the 24 h JTWC forecasts have mean FTEs that are slightly smaller than the mean CLIPER FTEs, the t-test values (Table 11) indicate undetermined skill relative to CLIPER, except at +12 h. The 48 h JTWC forecasts also have FTEs smaller than CLIPER FTEs at all times relative to the transition, but only the -48 h and +12 h time segments have statistically different mean FTEs (Table 11). Although the +12 h FTE difference of 118 n mi suggests that JTWC has skill 12 h after the transition, the track errors are rather erratic at +24 h and +36 h for some very small sample sizes. If larger samples at these times would show skill as at +12 h, it would indicate that JTWC does modify the forecast track once the new

Environmental Structure is established. In general, the 72 h JTWC forecasts (Fig. 22) have smaller mean FTEs than the mean CLIPER FTEs, except for -36 h prior to the transition when JTWC has slightly larger errors. None of these 72 h ($FTE_{JTWC} - FTE_{CLIPER}$) differences are statistically significant (Table 11), and after the transition time, the number of cases are too small to make any valid comparisons.

C. N/NO TO N/AW TRANSITIONS

The transition from N/NO to N/AW (Fig. 23) has the highest frequency of occurrence (45) of any of the transitions (Carr *et al.* 1995). As shown in Figs. 3a and 3b, this transition involves storms that are influenced by a north-oriented ridge to the east. The generally poleward track of the N/NO Pattern/Region changes to the northeastward tracks of the N/AW Pattern/Region. Due to the increased translation speed of the storms in the N/AW Pattern/Region, the possibility exists for large forecast errors if the transition is not recognized by the forecaster. This is illustrated in Fig. 23, in which the mean CLIPER and JTWC FTEs for the 48 h forecasts are as large as the 72 h FTEs of the previous transitions (over 350 n mi). The overall FTE trend is consistent with the previous transitions in that the CLIPER FTEs increase until transition time, which indicates the degree of difficulty is quite high. The 72 h forecast period is not included in Fig. 23 because the numbers of cases are too small (less than 10) for nine of 11 time segments. As suggested by the tracks in Fig. 3b, storms in the N/AW Pattern/Region often have recurved and lost tropical characteristics by 72 h after entering the N/AW Pattern/Region combination. For both the 24 h and 48 h forecasts, the mean JTWC FTEs are slightly smaller than the mean CLIPER FTEs (Table 12).

Table 12. Statistical summary for comparison of JTWC and CLIPER as in Table 10, except for the transition from the N/NO to the N/AW Synoptic Pattern/Region.

Time rel to trans	24 h forecasts						48 h forecasts						72 h forecasts					
		CLIPER			JTWC			CLIPER			JTWC			CLIPER			JTWC	
	t-test	$\bar{x}$	s	$n_{1,2}$	$\bar{x}$	s	*t*-test	$\bar{x}$	s	$n_{1,2}$	$\bar{x}$	s	*t*-test	$\bar{x}$	s	$n_{1,2}$	$\bar{x}$	s
-72	-0.695	94	57	13	80	45	-1.139	200	105	12	156	83	+0.496	264	157	8	300	132
-60	-1.141	142	84	19	109	94	-0.921	275	177	17	220	171	-0.472	514	346	13	452	323
-48	-0.901	101	55	28	88	53	-0.066	206	100	22	204	102	-1.654	430	183	13	309	190
-36	-1.082	124	84	33	104	65	-0.793	246	138	25	217	120	+0.470	390	286	8	453	249
-24	-0.863	129	102	34	110	78	-0.541	373	261	22	334	215	-0.644	784	456	6	606	500
-12	-1.427	176	106	34	141	96	-0.997	432	201	14	350	233	+0.439	411	220	2	483	74
+00	-0.733	200	120	25	177	101	-0.140	412	272	8	394	243	N/A	0	0	0	0	0
+12	-1.380	177	85	15	138	69	-0.827	299	292	2	125	57	N/A	0	0	0	0	0
+24	-0.308	162	133	8	143	113	N/A	221	0	1	16	0	N/A	0	0	0	0	0
+36	-0.447	139	111	2	100	54	N/A	0	0	0	0	0	N/A	0	0	0	0	0
+48	N/A	60	0	1	21	0	N/A	0	0	0	0	0	N/A	0	0	0	0	0

However, the two-sample *t*-test (Table 12) indicates that none of the mean 24 h or 48 h FTE differences are statistically significant at the 95% confidence level.

D. N/NO TO S/DR TRANSITIONS

The final transition to be discussed is from the N/NO to the S/DR Pattern/Region combination (Fig. 24). Twenty storms in the five-year period experienced this transition. The poleward motion in the N/NO Pattern/Region (Fig. 3a) is dramatically changed to westward in the S/DR Pattern/Region combination (Fig. 2a) as the storm comes under the influence of a east-west oriented subtropical ridge or another TC (Carr *et al.* 1995).

In contrast to the three other transitions, the 24 h forecasts in Fig. 24 do not have larger CLIPER FTEs before transition, which indicates the 24 h forecast degree of difficulty

does not increase. Notice also that the mean JTWC FTEs also steadily decrease throughout this transition. However, the *t*-test values (Table 13) indicate that the 24 h JTWC forecasts have undetermined skill compared to CLIPER.

Both the 48 h and 72 h CLIPER FTEs in Fig. 24 increase about 24 h before the transition, which indicates that the degree of difficulty for these forecasts does increase as in the other three transitions. It is encouraging that the 48 h JTWC forecasts do not dramatically change as the transition time is approached. While this seems to indicate the forecasts JTWC have skill, the -12 h FTE difference is the only value of the 48 h forecasts that the *t*-test indicates is statistically significant (Table 13). Perhaps a larger sample will show that JTWC has skill at other times during the transition from N/NO to S/DR.

Table 13. Statistical summary for comparison of JTWC and CLIPER as in Table 10, except for the transition from the N/NO to the S/DR Synoptic Pattern/Region.

Time rel to trans	**24 h forecasts**						**48 h forecasts**						**72 h forecasts**					
		CLIPER			JTWC			CLIPER			JTWC			CLIPER			JTWC	
	t-test	$\bar{x}$	s	$n_{1,2}$	$\bar{x}$	s	*t*-test	$\bar{x}$	s	$n_{1,2}$	$\bar{x}$	s	*t*-test	$\bar{x}$	s	$n_{1,2}$	$\bar{x}$	s
-72	-0.890	161	63	12	139	58	-0.890	322	144	12	272	131	+0.129	368	192	10	378	153
-60	-0.959	160	61	11	137	51	-0.739	281	77	11	252	105	+0.253	300	126	10	317	171
-48	-0.425	132	107	15	117	85	-0.207	205	118	15	196	120	-0.171	252	118	15	243	167
-36	-0.539	139	83	19	125	77	+0.165	220	121	18	227	134	+0.147	341	166	15	350	170
-24	-0.519	147	102	19	132	74	-1.407	307	190	17	229	127	-1.382	475	274	13	350	177
-12	-1.582	146	81	21	111	61	*-2.313*	326	167	17	210	122	*-2.121*	468	234	14	306	164
+00	-0.895	129	80	22	111	50	-1.216	256	95	17	209	128	*-2.075*	445	144	15	319	186
+12	-0.812	121	55	20	107	54	-1.111	253	133	17	207	107	-0.786	438	261	12	367	173
+24	+0.819	85	58	17	102	63	+0.036	200	174	15	202	123	-0.597	241	166	9	205	72
+36	-0.512	102	54	16	93	45	-1.439	225	165	13	150	90	-1.411	310	80	7	234	118
+48	-1.524	112	58	16	86	36	+0.048	163	96	10	165	92	+0.523	303	148	6	342	107

The 72 h forecasts have similar trends as the 48 h forecasts in that CLIPER has much larger mean FTEs than do the JTWC forecasts at 24 h before the transition, and the JTWC mean FTEs do not increase just before transition time. The largest mean JTWC FTE for the 72 h forecasts is actually at +12 h after the transition, vice at -12 h before transition, as was the general trend for other transitions. Only the -12 h and 0 h ($FTE_{JTWC} - FTE_{CLIPER}$) differences are significant according to the *t*-test values (Table 13) with sample sizes of 14 and 15 respectively, which suggests that the 72 h JTWC forecasts at these two times relative to the N/NO to S/DR transition have skill relative to CLIPER.

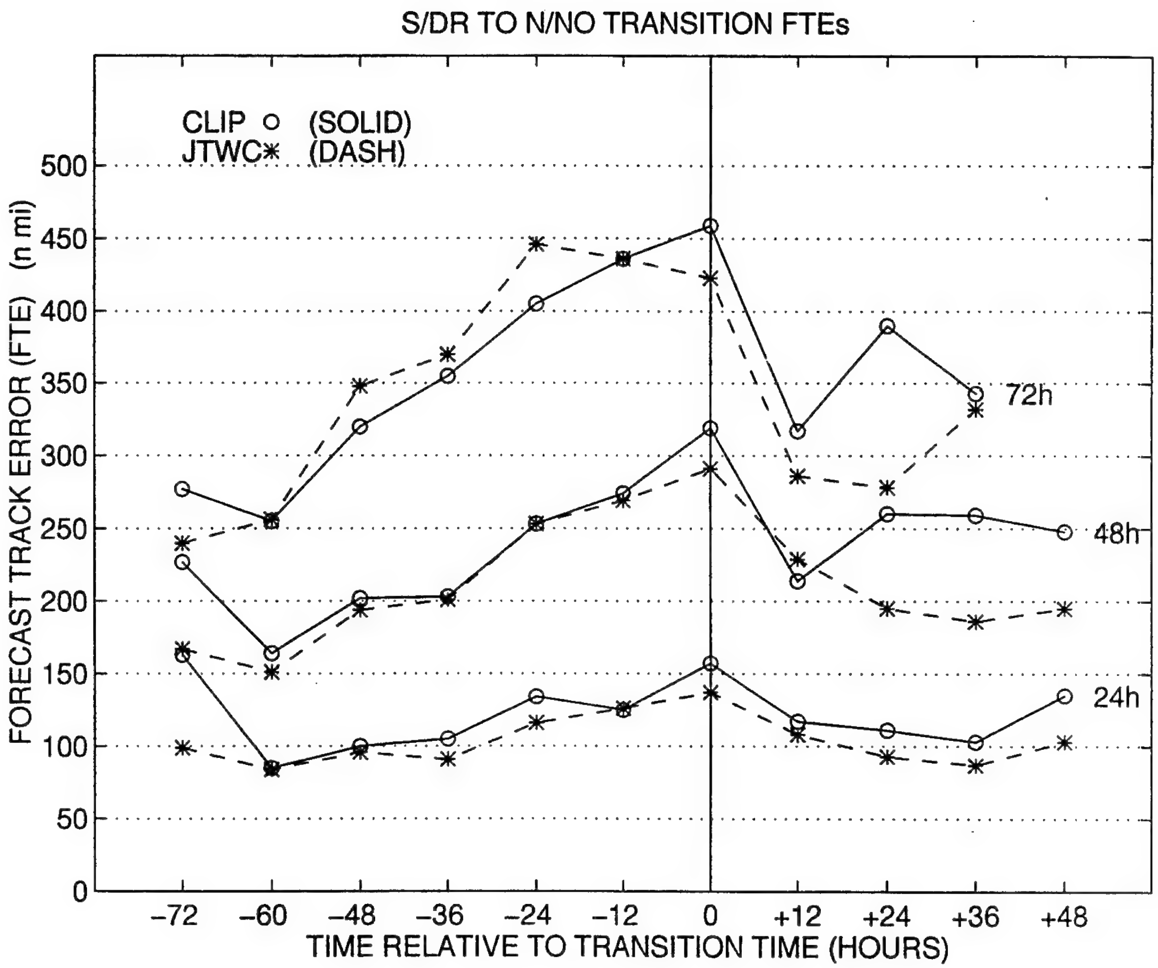

Figure 21 Forecast track errors (FTEs) of homogeneous comparisons between CLIPER (solid) and JTWC (dashed) for the transition from S/DR to N/NO Synoptic Pattern/Region combinations. See Table 10 for further details.

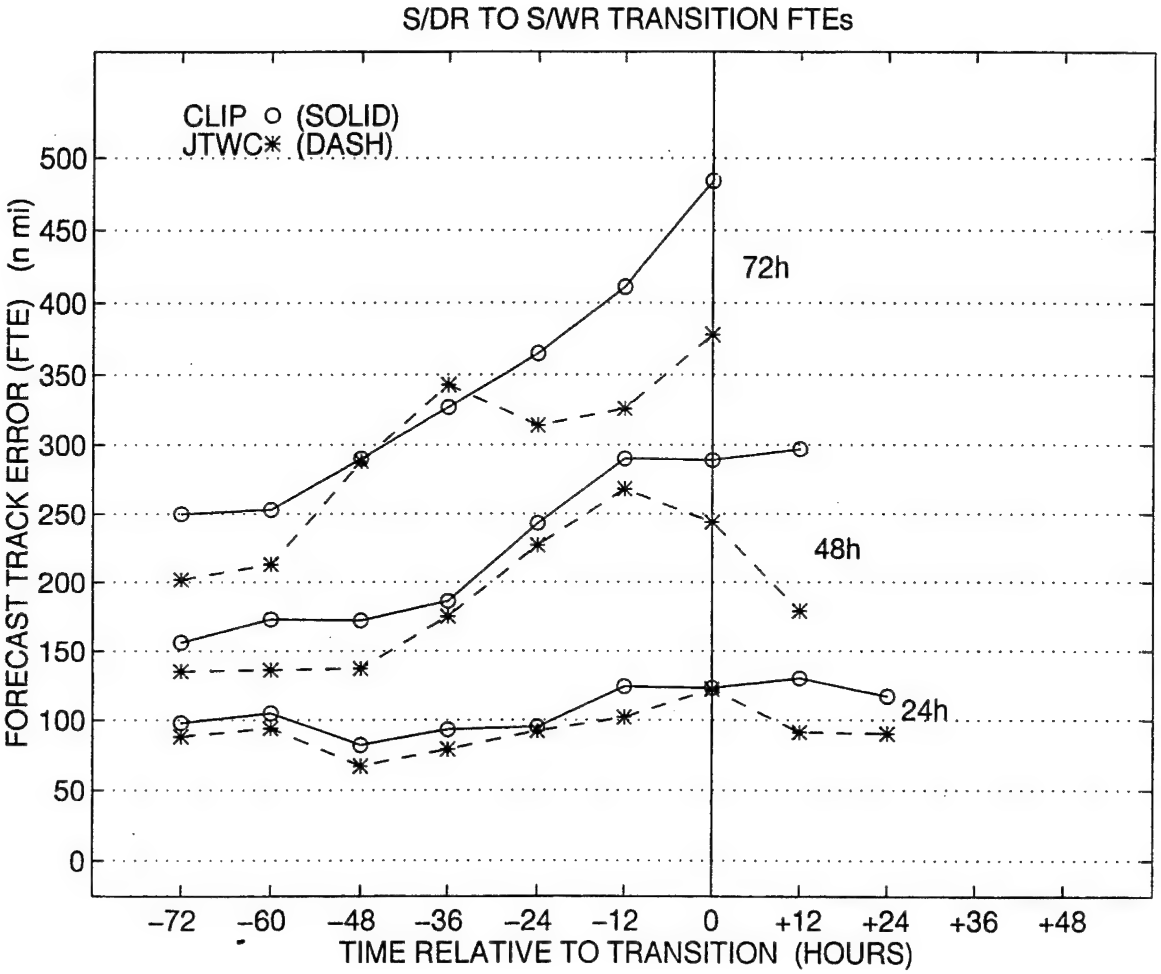

Figure 22 Forecast track errors (FTEs) of homogeneous comparisons between CLIPER (solid) and JTWC (dashed) for the transition from S/DR to S/WR Synoptic Pattern/Region combinations. See Table 11 for further details.

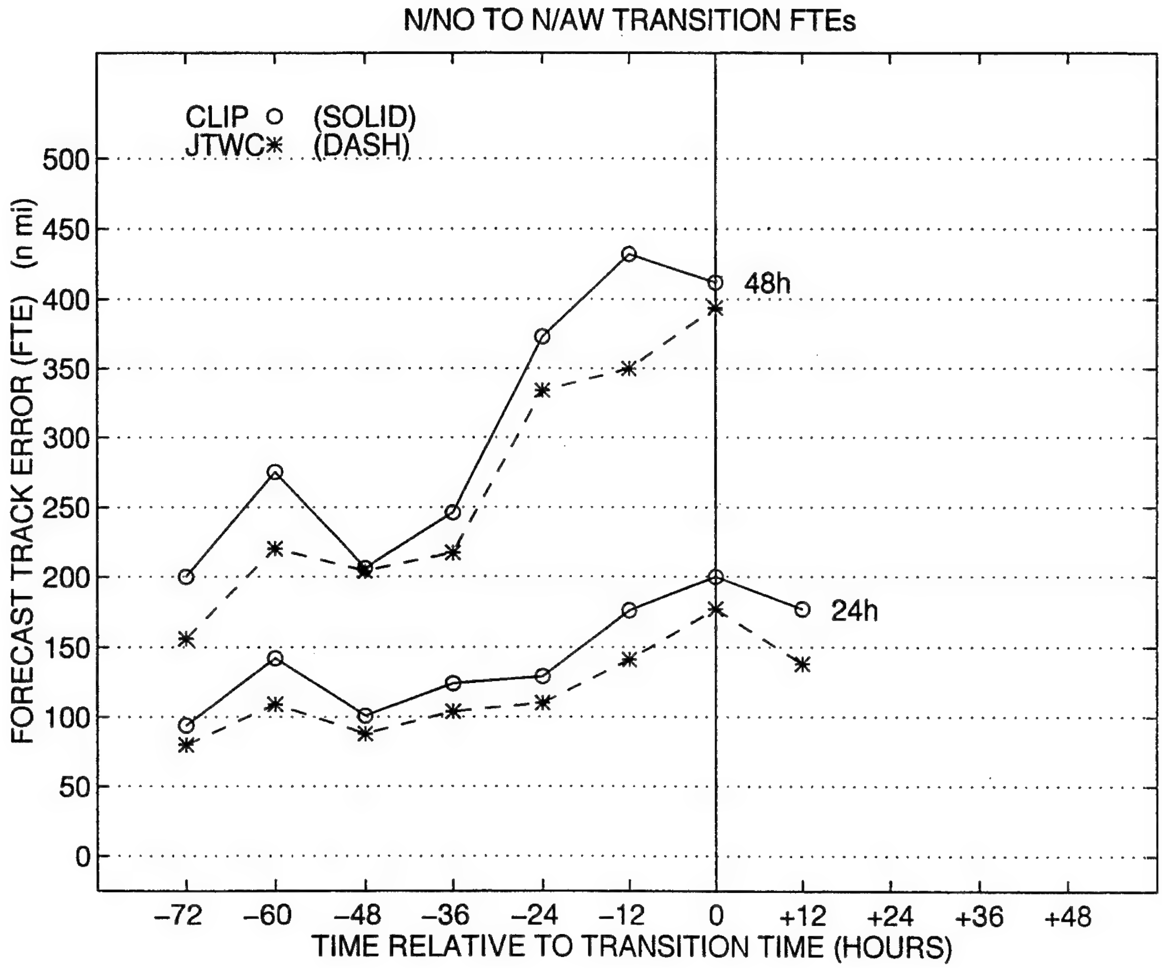

Figure 23 Forecast track errors (FTEs) of homogeneous comparisons between CLIPER (solid) and JTWC (dashed) for the transition from N/NO to N/AW Synoptic Pattern/Region combinations. See Table 12 for further details.

N/NO TO S/DR TRANSITION FTEs

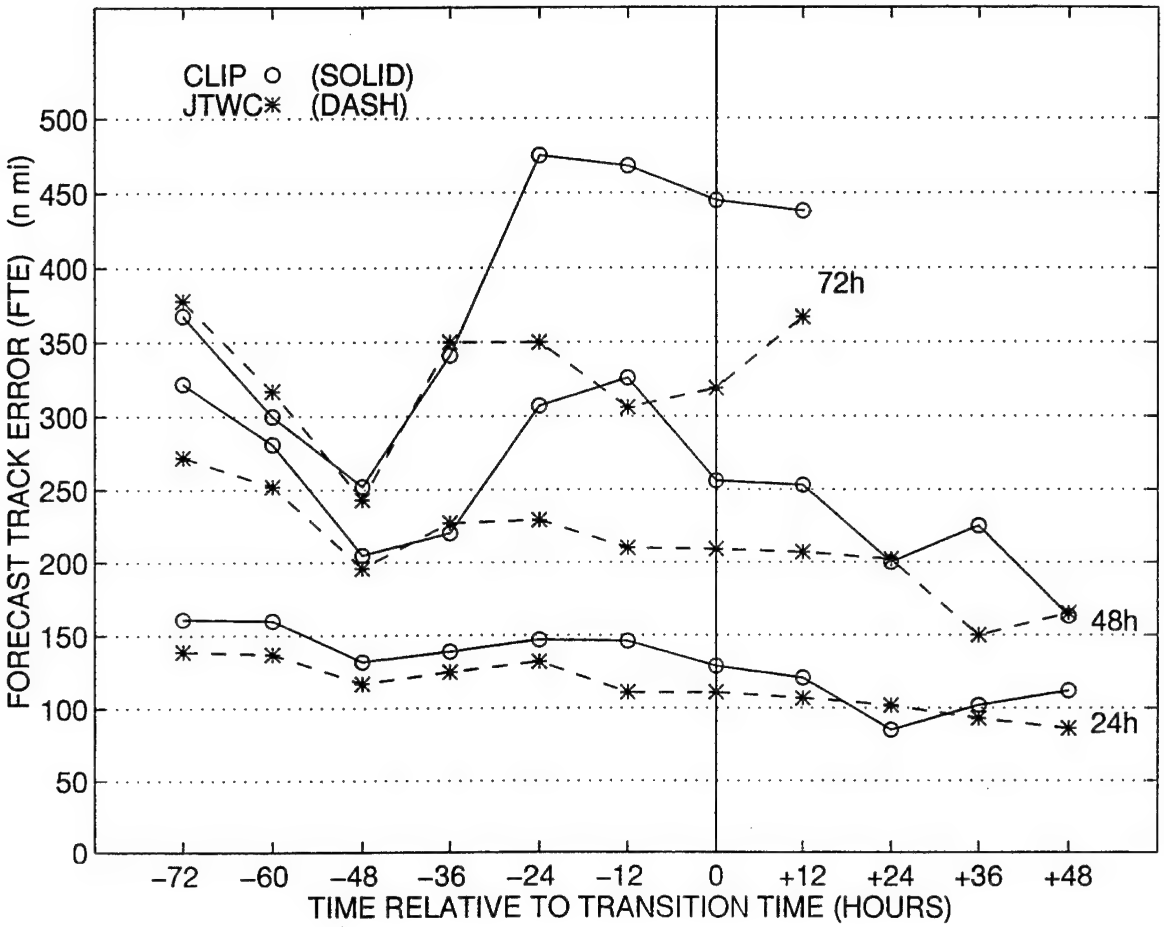

Figure 24 Forecast track errors (FTEs) of homogeneous comparisons between CLIPER (solid) and JTWC (dashed) for the transition from N/NO to S/DR Synoptic Pattern/Region combinations. See Table 13 for further details.

VI. JTWC CROSS-TRACK AND ALONG-TRACK ERRORS

Thus far, only forecast track errors (FTE) have been discussed. Cross-track error (XTE) and along-track error (ATE) defined in Fig. 1 may also be used in the verification of tropical cyclone track forecasts. Whereas the FTE verification assumes no directionality (error distribution that is circular about the mean FTE value), the ATEs and XTEs illustrate any directionality in the forecast error. For example, an ATE that is larger than the XTE would indicate a tendency for the translation speed (along-track) error to be a bigger problem than the path (cross-track) error. This would be important to know for setting of the warnings as to when a facility should begin preparations for the tropical cyclone strike. In addition, an elliptical (rather than a circular) dangerous semicircle for ship diversions would be more appropriate in such a situation. An important aspect of these ATE/XTE values is that they are calculated with respect to the best track positions, which are only known from a post-storm analysis. Although these ATE/XTE values are useful for assessing the JTWC forecast performance, the calculation with respect to the post-storm analysis track limits their potential use to adjust for likely JTWC errors in real time.

The 24 h, 48 h, and 72 h JTWC forecasts within each Synoptic Pattern/Region combination will now be evaluated in terms of the XTE and the ATE distributions for each Pattern/Region relative to the overall JTWC sample. The 24 h, 48 h, and 72 h JTWC errors for each Pattern/Region combination are assumed to have a bivariate standard normal distribution. The XTE and ATE values are first "transformed" into a new coordinate system with the new t axis lying along the maximum variance and the new s axis lying perpendicular to the t axis along the minimum variance. This transformed s-t coordinate system has a

rotation angle relative to the original positive XTE axis with positive (negative) angles indicating a counterclockwise (clockwise) rotation. After this rotation, the major axis of the error ellipse will lie along the *t* axis (maximum variance) and the minor axis will lie along the *s* axis (minimum variance). Given the assumption that these error distributions have bivariate standard normal distributions, the probability that a specified percentage (e.g., 90% in Figs. 25-31 at end of this chapter) of the errors will lie within ellipses with specific major and minor axes is given in standard statistical tables. More detailed information on the construction of the confidence error ellipses can be found in Chen (1991).

The 24 h, 48 h, and 72 h dangerous semicircles in the JTWC warnings presently use 120 n mi, 240 n mi, and 360 n mi (circular) for all storms, which presumably represents the long-term mean JTWC FTEs. Various alternatives are possible for selecting a comparable confidence interval for use with these elliptical ATE/XTE distributions. Since the median (50% confidence) FTE is typically less than the mean FTE (ATCR 1993), the percent confidence ellipse should be greater than 50%. Other values explored include: 50%, 75%, 90%, and 95% (shown in Figs. 25b-27b). Because the determination of each of the confidence ellipses is from standard normal distributions, the different confidence ellipses will be concentric about the 50% confidence ellipse of each of the three forecast periods (24 h, 48 h, and 72 h). The center of these 24 h, 48 h, and 72 h confidence ellipses is indicated by the "X" symbol (Figs. 25b-27b) and is determined by the mean XTE and mean ATE of each forecast period. Although the ellipses appear to have a nearly identical bias for each of the forecast periods, this is due to the scale of the figures. The mean XTEs for the JTWC (ALL) forecasts only vary from -7 n mi to -18 n mi, while the mean ATEs increase from -44 n mi (24

h) to -139 n mi (72 h) (Table 14). Scatter plots for the 24 h, 48 h, and 72 h JTWC (ALL) forecasts are shown in Figs. 25a, 26a, and 27a, respectively. When compared with their respective error ellipses (Figs. 25b, 26b, and 27b), these scatter plots clearly demonstrate the large variations in cross-track and along-track errors of individual storms. Notice the largest errors in each sample are not always well represented by these confidence ellipses. When the forecasts are stratified into the Pattern/Region combinations, those large forecast errors can dramatically change the shape of the error ellipses as compared to the JTWC (ALL) error ellipses.

Clearly the warnings would be raised earlier, or the ship diversion would have to be at a greater distance from the forecast position, if the risk is to be reduced by choosing higher (i.e., 90 or 95) percent confidence ellipses. It is important to note that the tropical storm may be weak or strong, so that the actual risk involves other factors than just the long-term mean JTWC FTE. The 90% confidence error ellipse illustrated in Figs. 25b, 26b, and 27b and in subsequent error distributions is selected as a likely upper bound. In practice, a smaller value such as 75% might be used, but this will depend on customer needs as well (asset values at risk, criticality of the military mission being threatened, etc.). Alternate confidence ellipses are easily generated for evaluating the risk versus cost, or inconvenience of a larger diversion, involved. Recall that the main purpose of the confidence ellipse comparisons below is to illustrate that the ATE/XTE distributions for the various Synoptic Pattern/Regions may differ considerably from those for JTWC (ALL), and have a directionality that would imply adoption of elliptical warning regions rather than circular regions.

Error ellipses will be displayed using 90% confidence levels with the usual statistical assumption that the sample data are bivariate standard normal distributions. However, this assumption may not be true for all ten Pattern/Region combinations, especially for the relatively small (below 100 cases) sample sizes. The 90% confidence ellipse for a standard normal distribution would imply that 90% of the data points (error values) should be within the ellipse, while the remaining 10% should be outside the ellipse. For those Pattern/Region combinations that do not have a standard normal distribution of ATE/XTEs, the expected percentages of error values inside and outside the error ellipse will not necessarily be valid. The generally large radii of the 90% confidence ellipses in Figs. 25b, 26b, and 27b relative to the 120, 240, and 360 n mi long-term mean JTWC FTEs are an indication (similar to large standard deviation values) that errors are spread beyond the ends of the bell-shaped curve of a standard normal distribution (Anderson and Sclove 1986). More analysis is required to determine a more appropriate error distribution function and further study is recommended.

A. ALL PATTERN/REGION COMBINATIONS

The mean XTE and mean ATE values, the radii of the 90% confidence ellipse major and minor axes, and the degrees of tilt of the ellipse relative to the positive XTE axis of the 24 h, 48 h, and 72 h JTWC forecasts for all Pattern/Region combinations will again be displayed in Figs. 28-31. The number of JTWC (ALL) cases for 24 h, 48 h, and 72 h in the five-year sample are 3432, 2712, and 2156, respectively. Each of the JTWC (Pattern/Region) error distributions will then be compared with these JTWC (ALL) distributions at 24 h, 48 h, and 72 h to illustrate where the Synoptic Environment classification may indicate a different directionality of the ATE/XTEs.

The mean XTE values at 24 h, 48 h, and 72 h are negative for the JTWC (ALL) sample (Table 14). Although these XTEs are small, this indicates that the JTWC (ALL) forecast positions are slightly left of the verifying best track positions (Fig. 25b). The mean ATE values are also negative and much larger, which indicates that the JTWC (ALL) track forecasts are typically behind the verifying position. These mean ATEs are equivalent to a slow bias of 1.8, 1.9, and 1.9 kt for 24 h, 48 h, and 72 h forecasts, respectively. Some of this apparent slow bias may be attributed to directional errors rather than a real along-track translation speed error. That is, a forecast translation of 10 kt of a storm actually moving at 10 kt will project onto the storm track as a negative ATE if the forecast track is either to the

Table 14. Mean cross-track errors ($\overline{XTE}$) and mean along-track errors ($\overline{ATE}$) in n mi for JTWC forecasts in ALL Patterns/Regions and in the S Pattern. Also listed are the radii (n mi) of the major (**MAJ**) and the minor (**MIN**) axes of the 90% confidence error ellipses, the degrees of tilt of the error ellipse from the positive XTE axis, and the sample count. Insufficient samples are available to estimate 48 h and 72 h error ellipses for the S/AW combination.

	$\overline{XTE}$	$\overline{ATE}$	**MAJ**	**MIN**	**DEG**	**COUNT**
JTWC (ALL)						
24 h	-13	-44	149	128	14	3432
48 h	-18	-92	281	240	12	2712
72 h	-7	-139	432	360	7	2156
S/DR						
24 h	-7	-35	131	123	10	1915
48 h	-10	-78	255	226	16	1639
72 h	-4	-114	398	334	9	1393
S/WR						
24 h	-18	-51	159	135	-0.1	150
48 h	-13	-97	320	214	-18	87
72 h	62	-146	567	291	-18	45
S/AW						
24 h	-41	-35	174	114	-19	30
48 h	0	0	0	0	0	0
72 h	0	0	0	0	0	0

left or right of the actual track (Fig. 1). Thus, these JTWC (ALL) XTE and ATE distributions indicate that for the "typical" tropical storm during 1989 to 1993, the JTWC forecasts were slightly left of storm track and about 1.9 kt slow. The major axes of the 90% confidence ellipses for these three forecast intervals (Table 14) are larger (149, 281, and 432 n mi) than the FTE values that JTWC uses for the standard dangerous semi-circles (120, 240, and 360 n mi). However, the minor axes are at most 8 n mi larger (128, 240, and 360 n mi).

These JTWC (ALL) error distributions will be used to compare with the error distributions for JTWC forecasts within specific Synoptic Pattern/Region combinations. If the 90% confidence ellipses of the XTE and ATE distributions for the Pattern/Regions depart significantly from those for JTWC (ALL), those JTWC forecasts during 1989-1993 had more of a directionality than the "typical" track forecast. That is, the major and minor axes of the 90% confidence ellipse illustrating the shape and orientation of the JTWC ATE/XTE errors for each Pattern/Region indicate the tendency for either larger or smaller along-track or cross-track errors as a function of the Synoptic Environment specifications of the Systematic Approach (Carr and Elsberry 1994).

B. S PATTERN

The S/DR Pattern/Region 90% confidence ellipses for 24 h, 48 h, and 72 h JTWC ATE/XTE are very similar in shape and size to the JTWC (ALL) ellipses (Fig. 28a). This similarity is expected because of the large fraction of the total sample of cases in the S/DR combination (1916, 1639, and 1393 for 24 h, 48 h, and 72 h, respectively). Although the mean XTEs for JTWC (S/DR) (Table 14) are negative for all three forecast intervals, they are even smaller than the mean XTEs for JTWC (ALL). These essentially zero mean XTE values

indicate that JTWC (S/DR) forecasts during 1989-1993 had no significant track path bias, i.e., the JTWC forecasts were as likely to be left of track as right of track for storms in the S/DR combination. Whereas the mean ATEs for storms in the S/DR combination are again negative (Table 14), the values are smaller than the mean ATEs of JTWC (ALL) for each forecast interval. This indicates that JTWC forecasts have generally been about 1.4 to 1.6 kt too slow for storms in the S/DR Pattern/Region during 1989-1993.

The major and minor axes of the 24 h, 48 h, and 72 h ellipses for JTWC (S/DR) are slightly smaller and more symmetrical than the axes for JTWC (ALL), which indicate that JTWC forecasts in the S/DR Pattern/Region have less bias and are likely to be more consistent than the "typical" TC. For these 90% confidence ellipses, the major and minor axes are slightly larger and either equal or smaller than the standard 120, 240, and 360 n mi FTE values that JTWC presently uses to calculate dangerous circle radii. If the confidence level was reduced to say 75%, the major and minor axes would be decreased to (92, 86), (178, 156), and (278, 234) n mi for 24 h, 48 h, and 72 h, respectively. These differences may be significant enough to reduce the dangerous circle radii that JTWC would specify while the storm is in the S/DR Pattern/Region.

Since the JTWC ATE/XTE for storms in the S/WR Pattern/Region have small sample sizes (150, 87, and 45 at 24 h, 48 h, and 72 h, respectively), the errors are less likely to have a normal distribution as assumed for estimating the 90% confidence ellipses (Fig. 28b). Whereas the 24 h forecast error ellipse is very similar in shape and size to the JTWC (ALL), the 48 h and 72 h forecast error ellipses are more elongated in the cross-track direction and compressed in the along-track direction. As in the case of CLIPER (ALL), the 24 h and 48

h JTWC forecasts for the S/WR combination are slightly left of track and have a similar (apparent) slow bias of about 2 kt (Table 14). However, the mean XTE of the 72 h JTWC forecasts in S/WR is 62 n mi right of track as well as being 2 kt slow. Such a 72 h JTWC error could arise if the storm in the S/WR combination subsequently recurves and accelerates to the northeast (i.e., transition to the S/AW Pattern/Region) at an earlier time and a more rapid translation speed than JTWC forecast. If JTWC did not forecast a sharp recurvature, the XTE could then be more to the left than the JTWC (ALL) ellipse.

Whereas caution is advised because of the low number of cases (45) at 72 h, this error distribution ellipse indicates a potential area for improvement for the JTWC forecasters. Because all of the ellipses have a negative tilt and all of the major axes are larger than the axes for JTWC (ALL), the dangerous circle radii specified by JTWC might be adjusted for storms in the S/WR Pattern/Region to account for the larger XTE values of the 72 h forecast ellipse. As discussed previously in Chapters III and IV, the implication is that this S/WR Pattern/Region is more difficult to forecast.

Since storms do not usually remain in the S/AW Pattern/Region more than 24 h, not enough 48 h and 72 h JTWC forecasts are available to make any valid conclusions about the ATE/XTE distributions in this Pattern/Region (Table 14). The 24 h JTWC forecasts in the S/AW combination have a mean XTE = 41 n mi to the left and mean ATE = 35 n mi behind the verifying position (Table 14). A further leftward displacement of the JTWC (S/AW) errors is attributed to the larger major axis than for JTWC (ALL). If these forecast track displacement trends of the 24 h error ellipse were continued at 48 h and 72 h, the error distributions for JTWC would be quite large.

C. N PATTERN

The JTWC forecasts of storms in the N/NO Pattern/Region have larger mean XTEs and ATEs than the mean values for JTWC (ALL) (Table 15). These larger mean ATEs are equivalent to an apparent slow bias of 2.3 kt, 2.7 kt, and 2.8 kt for 24 h, 48 h, and 72 h forecasts, respectively. The larger negative mean XTE values indicate that the JTWC forecasts of storms in N/NO are slightly more to the left of the storm track than for the JTWC (ALL). Such slow and to the left JTWC errors for the N/NO storms may be attributed to an expectation by JTWC forecasters that the north-oriented tracks (Fig. 3a) are recurvature tracks that will turn northeastward with an acceleration. All of the N/NO 90% confidence error ellipses (Fig. 29a) are larger than for JTWC (ALL), which implies that the NO Region is more difficult to forecast than the average TC. Dangerous circle radii based on the 90% confidence ellipse would have to be increased for JTWC forecasts in this Pattern/Region

Table 15. Mean cross-track error ($\overline{XTE}$) and mean along-track error ($\overline{ATE}$) comparison as in Table 14, except for N Pattern.

	$\overline{XTE}$	$\overline{ATE}$	MAJ	MIN	DEG	COUNT
JTWC (ALL)						
24 h	-13	-44	149	128	14	3432
48 h	-18	-92	281	240	12	2712
72 h	-7	-139	432	360	7	2156
N/NO						
24 h	-24	-55	162	124	19	701
48 h	-37	-131	327	244	25	536
72 h	-32	-202	482	406	25	360
N/AW						
24 h	-15	-80	222	139	11	109
48 h	0	0	0	0	0	33
72 h	0	0	0	0	0	16

because the major axis values of 162, 327, and 482 n mi are considerably larger than 120, 240, and 360 n mi values presently used.

The sample sizes of JTWC forecasts of storms in the N/AW Pattern/Region are small for forecast periods of 48 h (33) and 72 h (16), which prevents any valid estimates of the probability ellipses (Table 15). However, the sample of 24 h JTWC forecasts includes 109 cases, and the 90% confidence error ellipse is elongated along the cross-track axis (Fig. 29b). The 24 h JTWC forecasts have a mean ATE equivalent to a 3.3 kt slow bias. The major axis of the 24 h error ellipse is oriented almost parallel to the cross-track axis and is quite large (222 n mi). If the dangerous circle radii were based on these 90% confidence ellipses, the circles would have to be expanded to account for the large variability in the cross-track errors. Notice that the N/AW tracks in Fig. 3b have a variety of directions, which may contribute to the JTWC cross-track errors.

D. G PATTERN

The mean ATEs of the JTWC forecasts for storms in the G/NO Pattern/Region are all negative and larger than the JTWC (ALL) values (Table 16), which implies that the JTWC forecasts are even farther behind the best-track positions of the storms in this Pattern/Region. This apparent slow bias is equivalent to 2.7 kt, 2.3 kt, and 2.7 kt for 24 h, 48 h, and 72 h JTWC forecasts, respectively. Only the 72 h forecast period has a positive XTE, which places the mean 72 h JTWC forecast right of track for this G/NO Pattern/Region. Early portions of the tracks in G/NO tend to be cyclonically curved (Fig. 4c) especially as small storms rotate around the gyre. Also, a significant number of these TCs underwent Monsoon Gyre-TC interaction (see Carr and Elsberry 1994), which involves an accelerating cyclonic turn toward

Table 16. Mean cross-track error ($\overline{XTE}$) and mean along-track error ($\overline{ATE}$) comparison as in Table 14, except for the G Pattern.

	$\overline{XTE}$	$\overline{ATE}$	MAJ	MIN	DEG	COUNT
JTWC (ALL)						
24 h	-13	-44	149	128	14	3432
48 h	-18	-92	281	240	12	2712
72 h	-7	-139	432	360	7	2156
G/NO						
24 h	-10	-65	178	151	35	231
48 h	-22	-109	309	292	-38	175
72 h	17	-191	460	410	51	132
G/DR						
24 h	-21	-21	155	135	75	122
48 h	-54	-21	278	195	-74	103
72 h	-30	-8	400	308	-52	92

the west-southwest before turning north. If the JTWC forecaster does not recognize this cyclonic rotation tendency, the JTWC forecast might be expected to be to the right of the actual position. All of the 90% confidence ellipses for the G/NO Pattern/Region (Fig. 30a) are larger than the ellipses of JTWC (ALL), which implies that the dangerous circle radii perhaps should be larger for this Pattern/Region. The combination of a slow bias and slightly larger major axis oriented in the along-track direction would suggest a more oblong danger area for storms in the G/NO combination.

In the G/DR Pattern/Region, the 48 h and 72 h JTWC forecasts have smaller error ellipses, smaller mean ATEs, and slightly larger mean XTEs than the respective counterparts from JTWC (ALL) (Fig. 30b). Since the G/DR 24 h 90% confidence error ellipse appears to be only slightly larger than the 24 h JTWC (ALL) ellipse, the difference is not likely to be statistically significant. The orientations of the G/DR error ellipses have a negative tilt and are centered close to zero since the mean ATEs are close to zero and the mean XTEs are also

relatively small (Table 16). Overall, the JTWC forecasts in the G/DR Pattern/Region appear to be the more accurate based on these mean XTEs and ATEs, and the minor axes of the error ellipses, when compared with the JTWC (ALL) forecasts. However, a reduction of the dangerous circle radii may not be justified at the 90% confidence level because of the large major axes (Table 16) that exceed the 120, 240, and 360 n mi values presently used in the standard JTWC dangerous circle radii.

The number of verifiable JTWC forecasts in the AW Region of the G Pattern is too small (less than ten) to construct confidence ellipses.

E. M PATTERN

Although the JTWC forecasts in the Southerly Flow (SF) and Northerly Flow (NF) Regions of the Multiple (M) Cyclone Pattern have sample sizes of 78 or less, error ellipses will be estimated for a tentative illustration of the error distributions. No significant differences from the JTWC (ALL) mean ATE and XTE values are found for the JTWC (M/SF) forecasts (Table 17). However, the JTWC forecasts in the M/SF Pattern/Region have error ellipses that are more elongated with negative tilts, especially at 48 h (Fig. 31a). Although the 72 h ellipse is much larger than the 72 h ellipse of JTWC (ALL), this ellipse is based on a relatively small sample size of 37. Whereas a valid comparison between JTWC (M/SF) and JTWC (ALL) should include more cases, the orientation of these error ellipses along the general storm tracks in the M/SF Pattern/Region (Fig. 5a) may be realistic. If the JTWC forecaster does not anticipate the accelerated motion between the western TC and the subtropical ridge to the east, the JTWC track forecasts at this stage could be slow. However, the M/SF Pattern/Region is transient as the TC tends to move quickly through the Region,

Table 17. Mean cross-track error ($\overline{XTE}$) and mean along-track error ($\overline{ATE}$) comparison as in Table 14, except for the M Pattern.

	$\overline{XTE}$	$\overline{ATE}$	MAJ	MIN	DEG	COUNT
JTWC (ALL)						
24 h	-13	-44	149	128	14	3432
48 h	-18	-92	281	240	12	2712
72 h	-7	-139	432	360	7	2156
M/SF						
24 h	-18	-41	172	121	-15	64
48 h	-13	-68	352	209	-58	48
72 h	8	-128	541	428	-29	37
M/NF						
24 h	4	-72	131	96	13	78
48 h	2	-189	302	203	12	69
72 h	5	-382	565	281	9	64

and then decrease (or at least not continue to increase) in translation speed. If the JTWC forecaster does not recognize this unusual post-recurvature behavior, a JTWC forecast that relies heavily on persistence could subsequently be too fast and to the left, after having been too slow and to the right earlier.

In the NF Region of the M Pattern, the JTWC forecasts have the largest mean ATEs (Table 17), with equivalent slow bias values increasing from 3 kt at 24 h to 5.3 kt at 72 h. This indicates that JTWC has more difficulty with the along-track speed for storms in the M/NF Pattern/Region, probably due to the complexity and non-climatological aspects of the storm tracks in the M/NF combination (Fig. 5b). An example of a cyclone in the M/NF combination with large errors is Typhoon Seth during 1991. Whereas JTWC forecast a recurvature, Typhoon Seth did not recurve, which lead to large 72 h errors. The near-zero mean XTEs indicate that the JTWC forecasts have no bias in cross-track (or path) errors. However, the large elongated ellipse for the 72 h JTWC forecasts (Fig. 31b) shows the large

variability of the error distribution. If this distribution was sustained with a larger sample size than 64 (Table 17), the radii of the dangerous circles would have to be increased for storms in the NF Region.

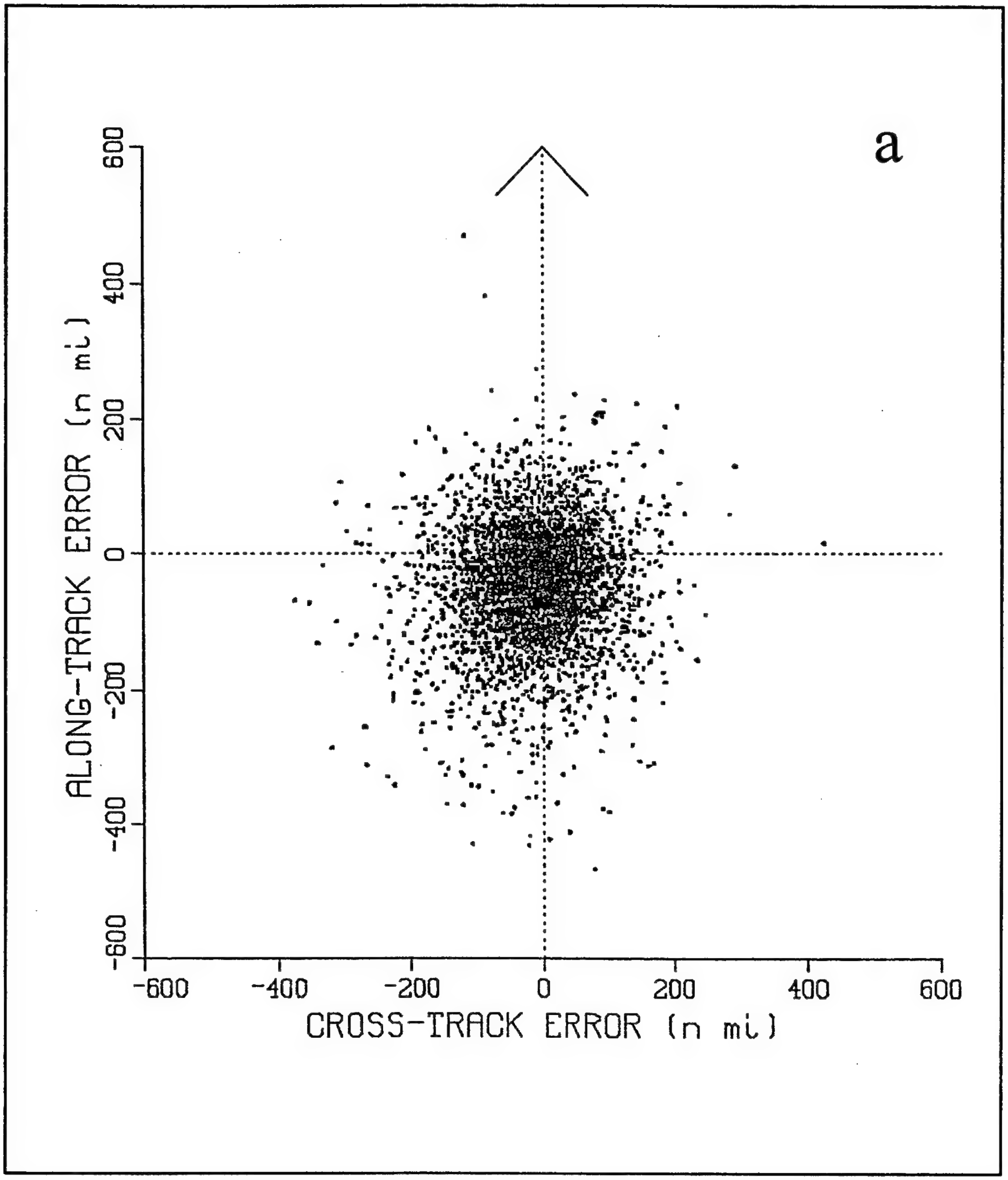

Figure 25a Scatter plot of 24 h JTWC cross-track errors (XTE) (x axis) and along-track errors (ATE) (y axis) in n mi for ALL Pattern/Region combinations. The center of the cross-hairs represents the location of the TC and the dots represent the values of the XTE and ATE values of the JTWC forecasts. The arrow pointing toward the top of the page indicates the direction of TC motion.

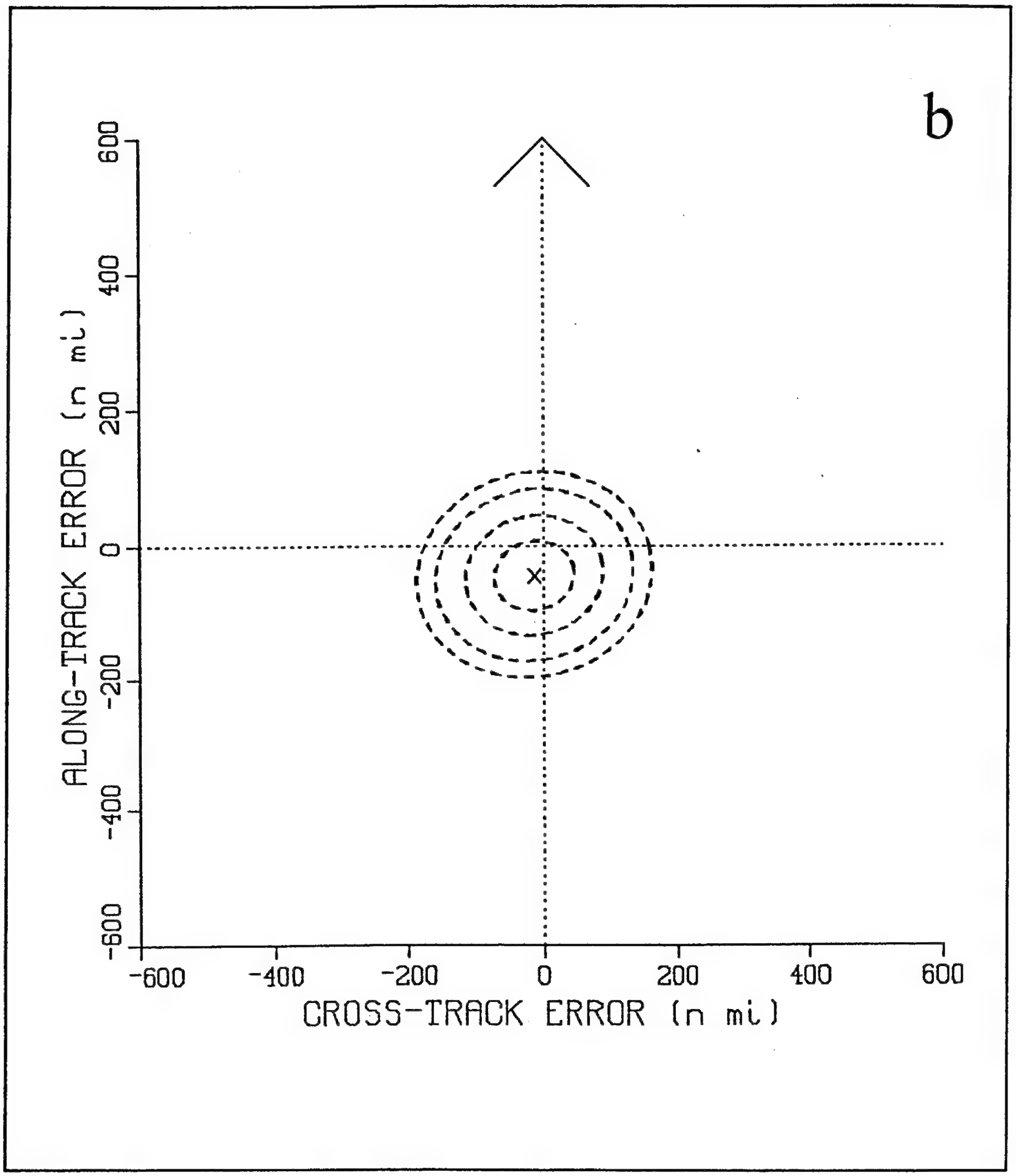

Figure 25b Confidence ellipses of 50% (innermost ellipse), 75%, 90%, and 95% (outermost ellipse), respectively, for JTWC 24 h cross-track errors and along-track errors which coincide with Fig. 25a (scatter plot). The "X" indicates the location of the 24 h JTWC (ALL) mean XTE and mean ATE.

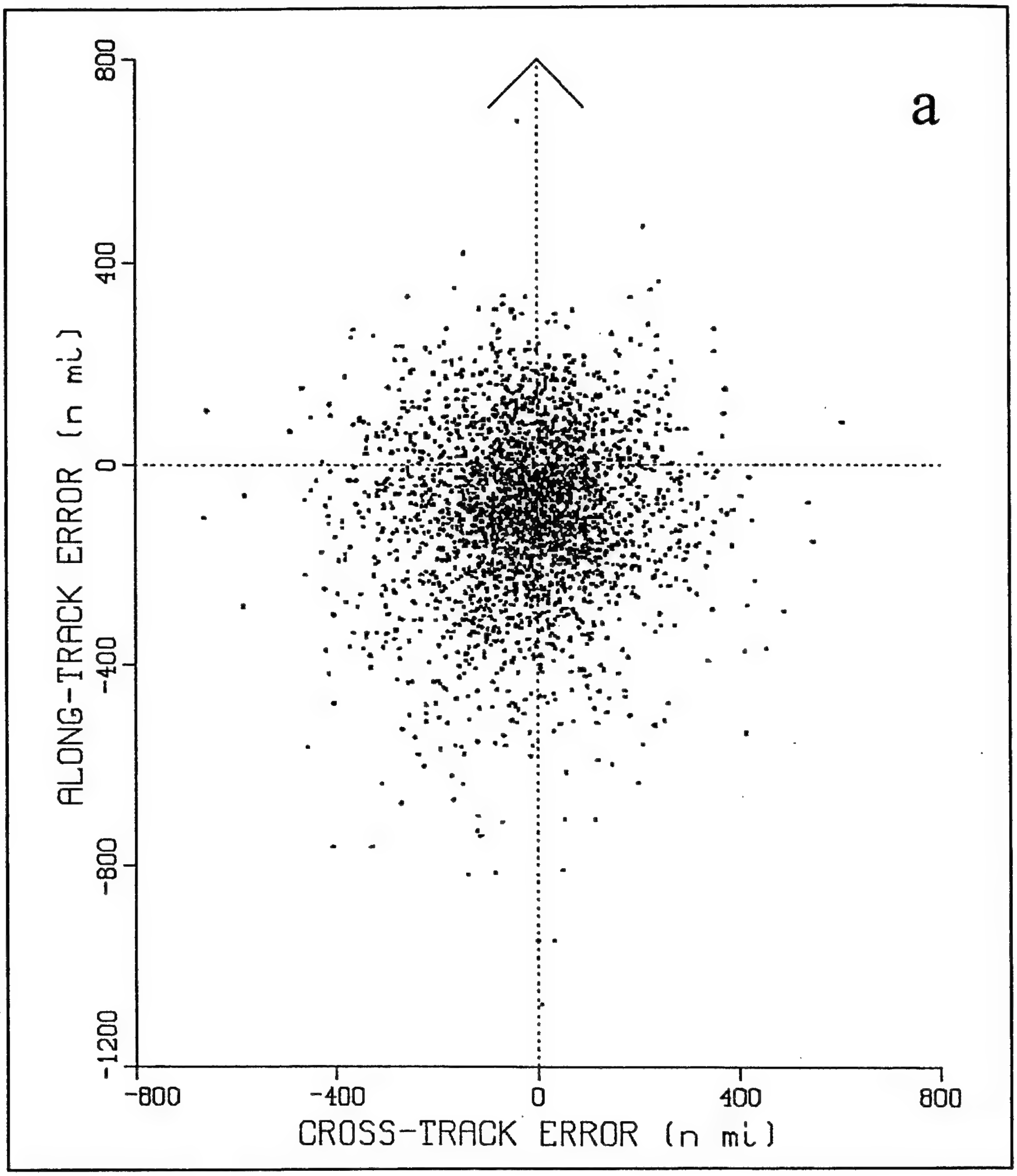

Figure 26a Scatter plot of JTWC (ALL) cross-track and along-track errors as in Fig. 25a, except for 48 h forecasts.

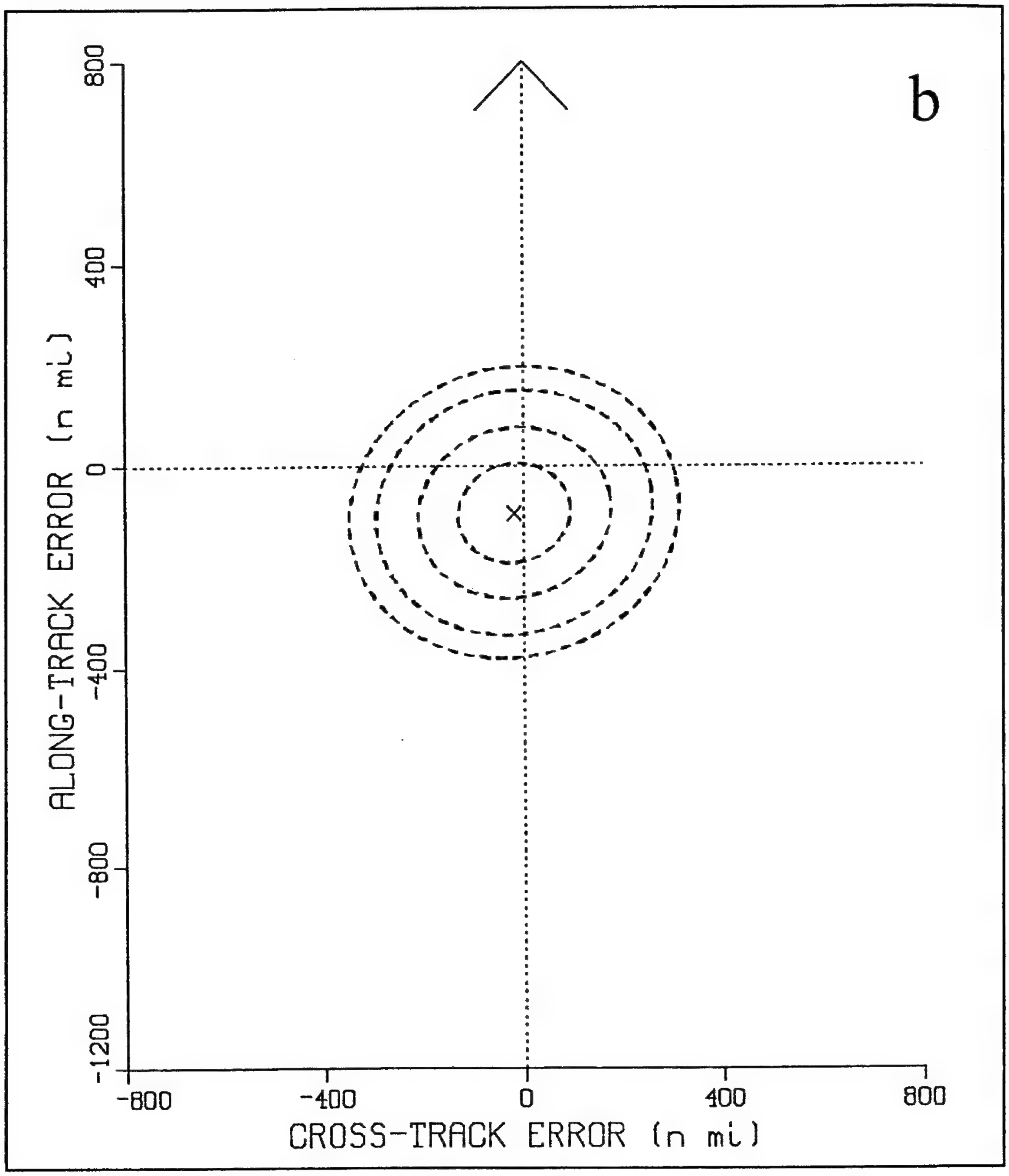

Figure 26b Confidence ellipses as in Fig. 25b, except for 48h JTWC (ALL) forecasts.

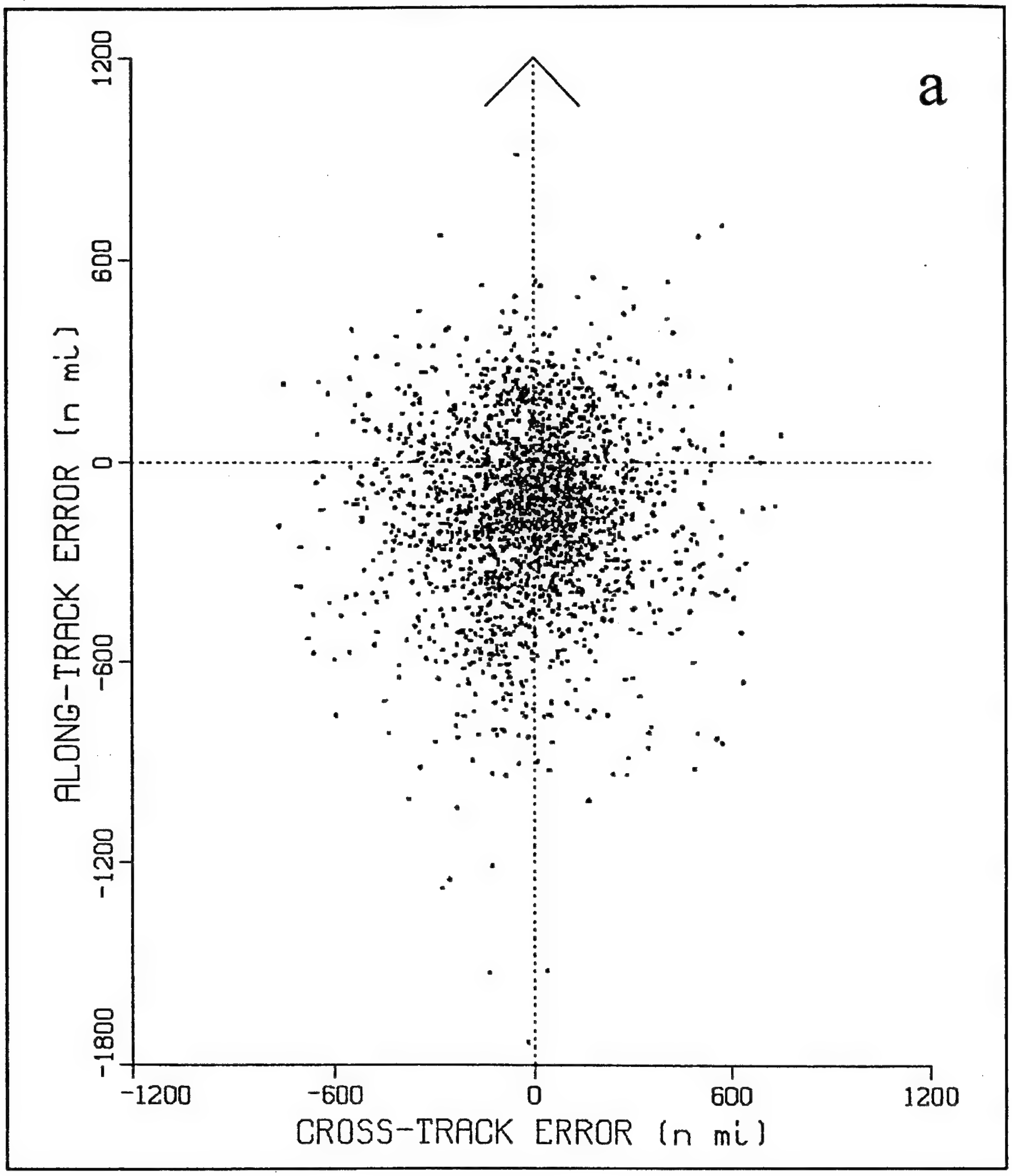

Figure 27a Scatter plots of JTWC (ALL) cross-track and along-track errors as in Fig. 25a, except for 72 h forecasts.

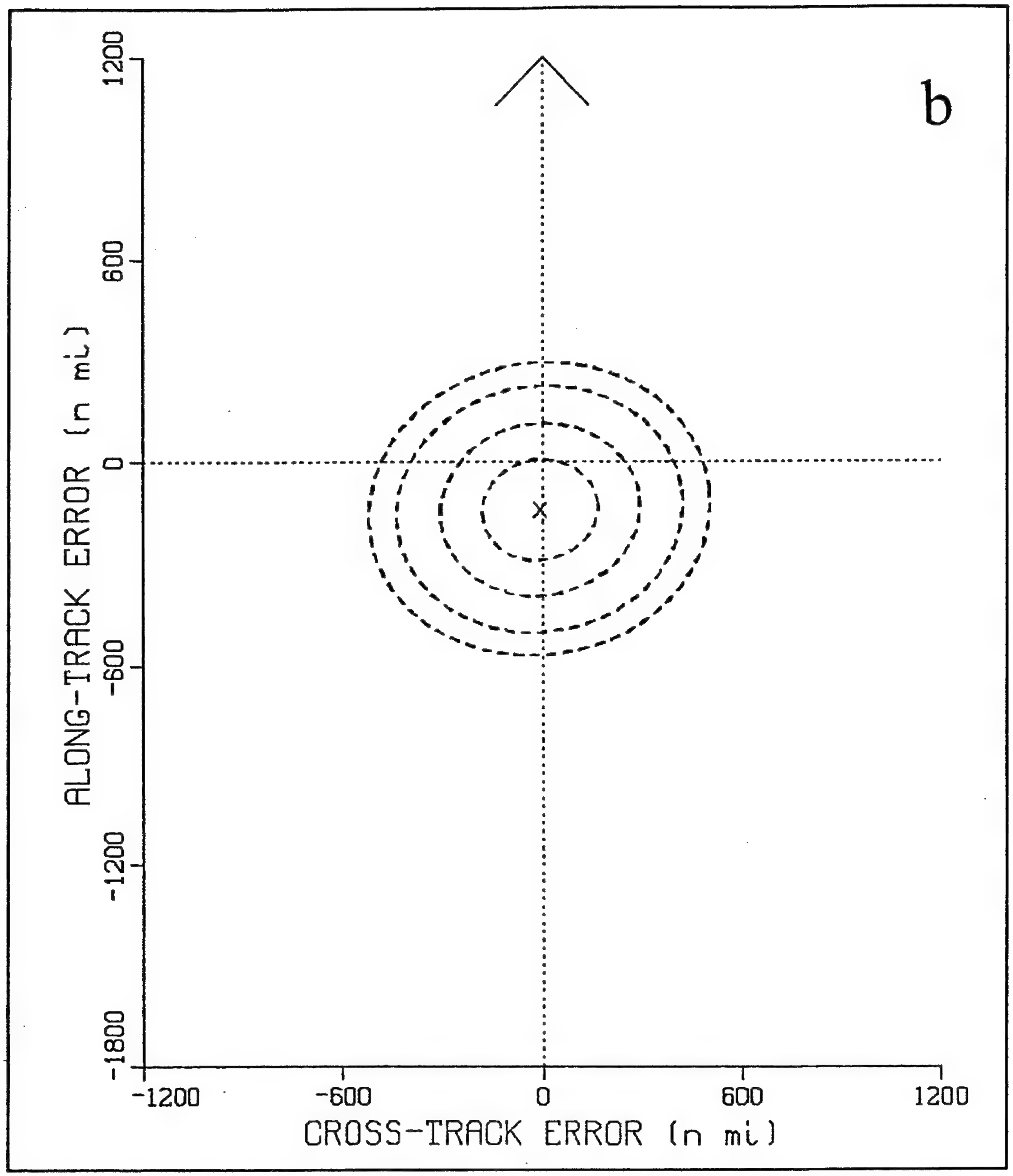

Figure 27b Confidence ellipses as in Fig. 25b, except for 72h JTWC (ALL) forecasts.

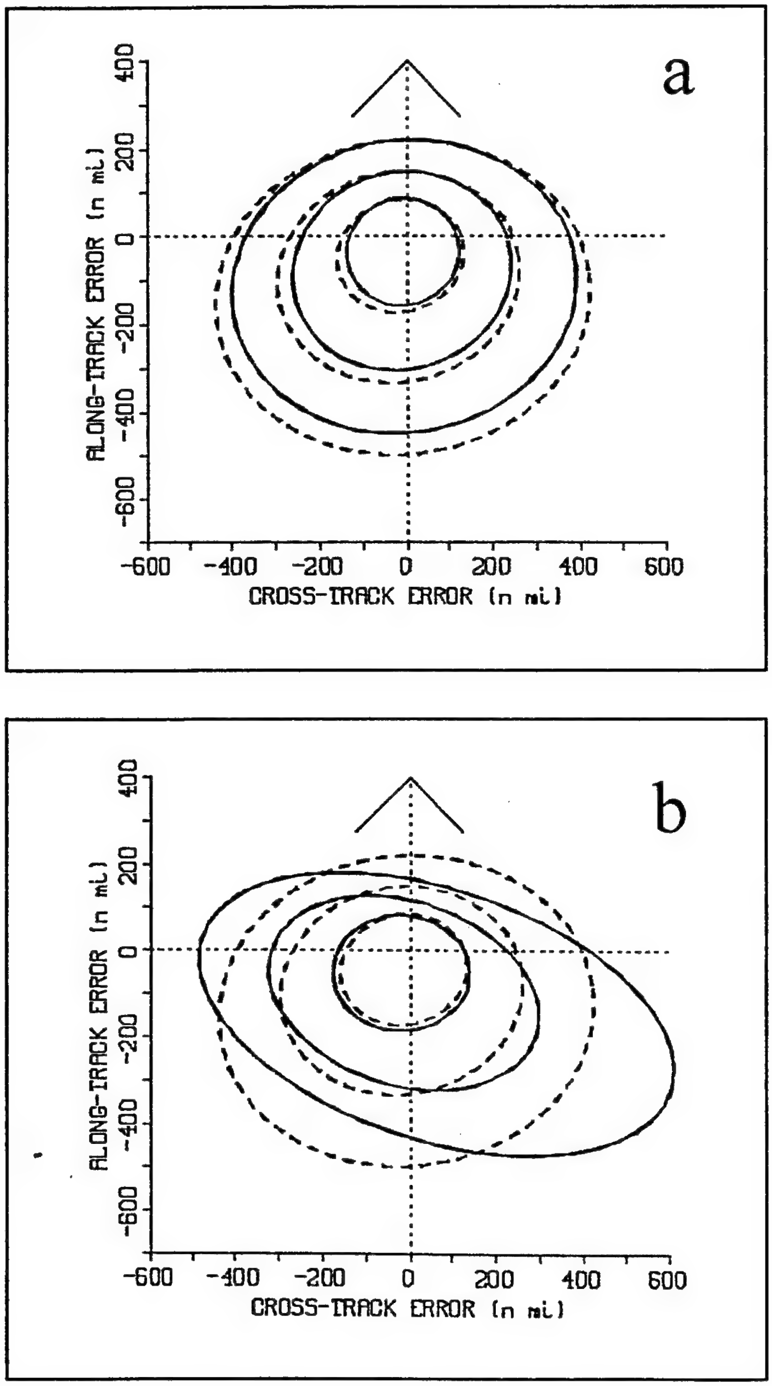

Figure 28 JTWC Standard (S) Synoptic Pattern (solid) and JTWC (ALL) Pattern/Region combinations (dashed) 90% confidence ellipses for 24 h (innermost ellipses), 48 h (middle ellipses), and 72 h (outermost ellipses) forecasts for the (a) Dominant Ridge (DR) and (b) Weakened Ridge (WR) Regions. Cross-track errors and along-track errors in n mi. See Table 14 for further details.

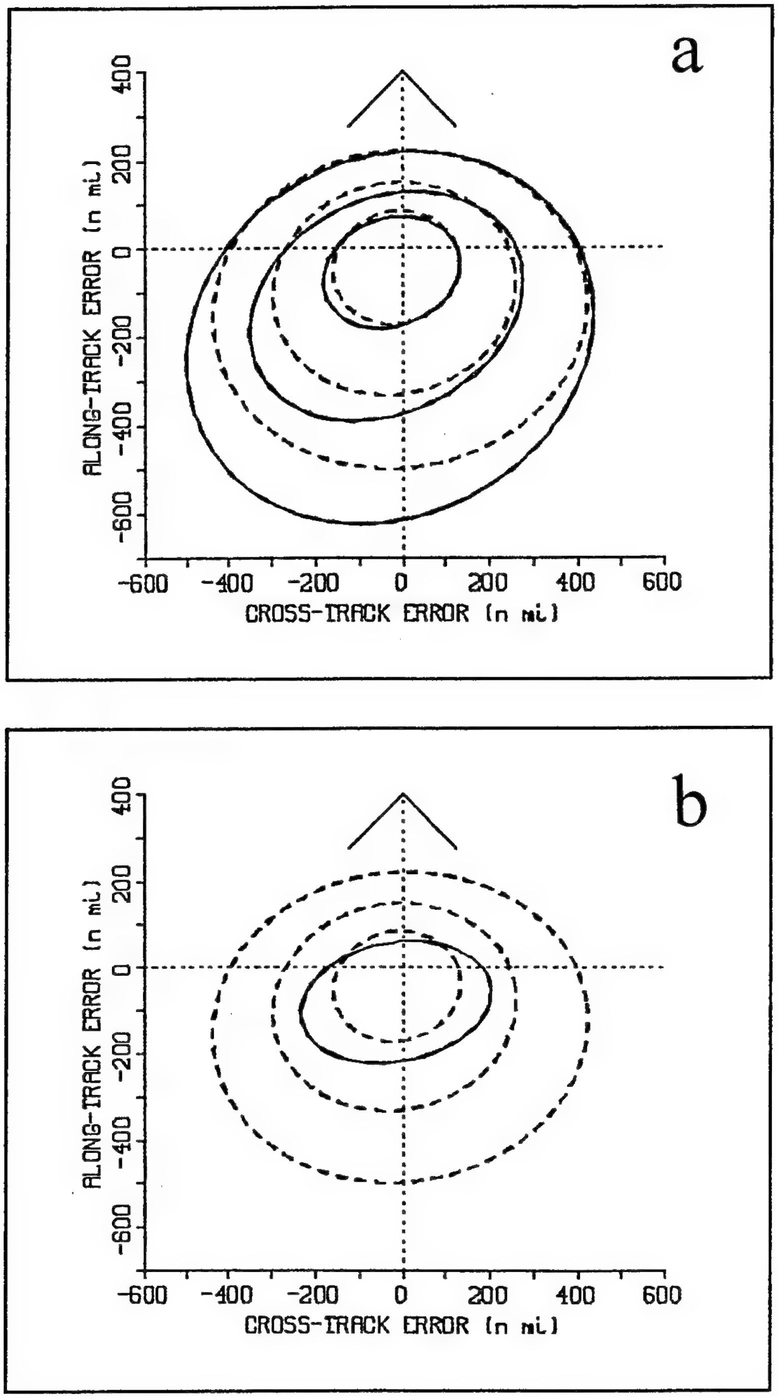

Figure 29 Confidence ellipses (90%) for JTWC as in Fig. 28, except for North-oriented (N) Synoptic Pattern and the (a) North-Oriented (NO) and (b) Accelerating Westerlies (AW) Regions. See Table 15 for further details.

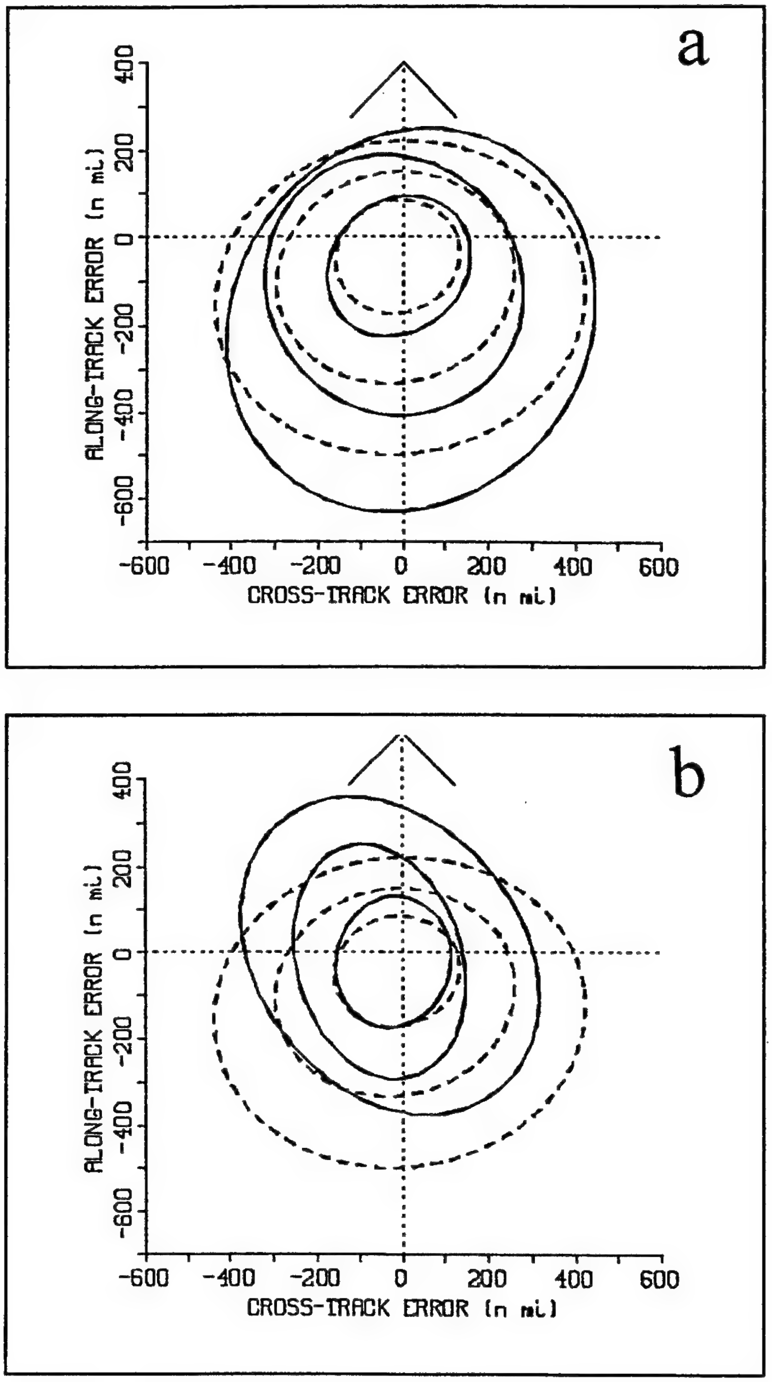

Figure 30 Confidence ellipses (90%) for JTWC as in Fig. 28, except for Gyre (G) Synoptic Pattern and the (a) North-Oriented (NO) and (b) Dominant Ridge (DR) Regions. See Table 16 for further details.

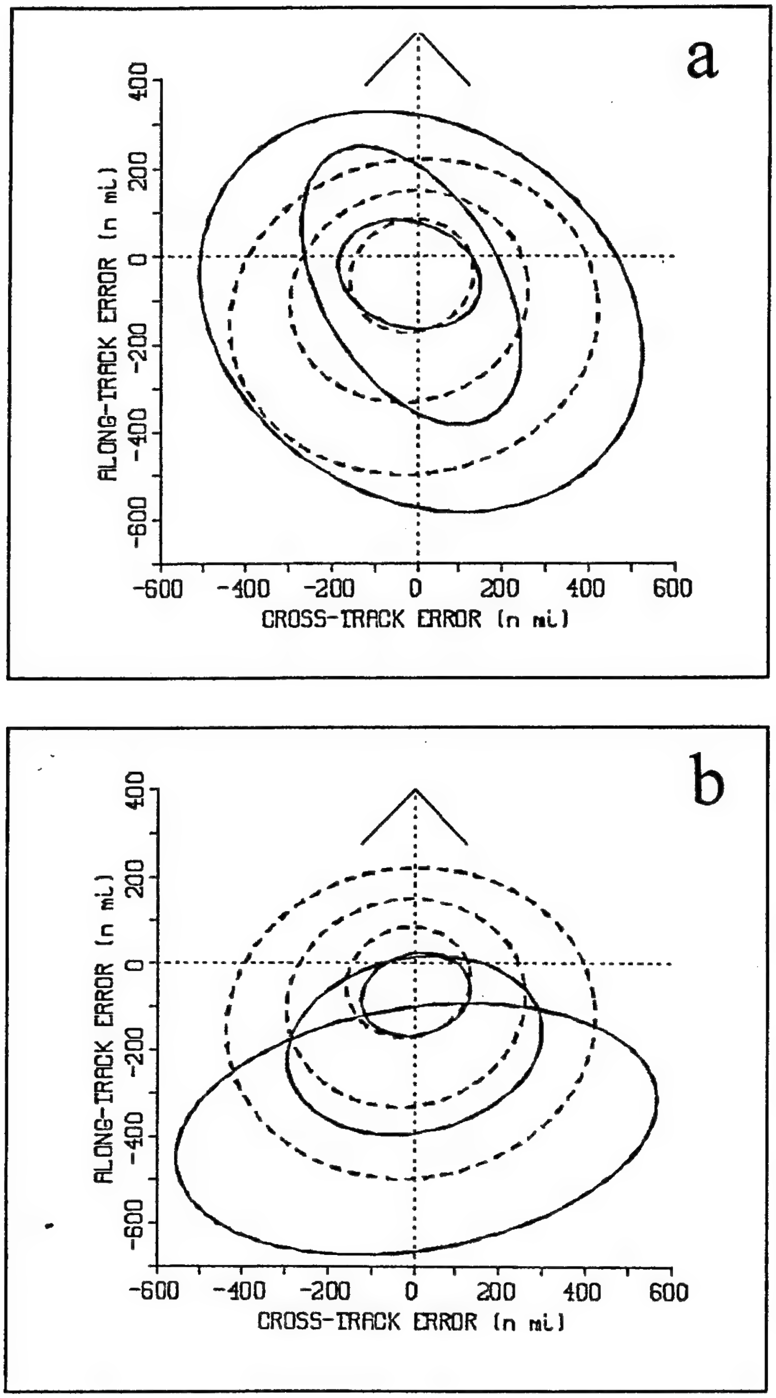

Figure 31 Confidence ellipses (90%) for JTWC as in Fig. 28, except for Multiple (M) Cyclone Synoptic Pattern and the (a) Southerly Flow (SF) and (b) Northerly Flow (NF) Regions. See Table 17 for further details.

VII. CONCLUSIONS AND RECOMMENDATIONS

The Synoptic Environment for western North Pacific tropical cyclones can be defined in terms of ten Synoptic Patterns and Regions in the Systematic Approach of Carr and Elsberry (1994). These ten Pattern/Region combinations have characteristic tracks that are displayed in Figs. 2 through 5 from Carr *et al.*(1995). The dramatic differences in tracks for these different Synoptic Patterns/Regions suggest that the degree of difficulty in forecasting the tropical cyclone track may be characterized in terms of the Synoptic Environment.

Varying degrees of forecast difficulty are demonstrated by comparing the Forecast Track Errors (FTEs) of the operational CLImatology and PERsistence (CLIPER) technique in the separate Patterns and Regions with the overall CLIPER FTEs for the five-year sample of Carr *et al.* (1995). Storms in the Dominant Ridge (DR) Region of the Standard (S) or the Gyre (G) Synoptic Patterns are demonstrated to be the least difficult to forecast because they have 72 h CLIPER FTEs less than the overall CLIPER FTEs. The most difficult 72 h forecasts are for storms in the Weakened Ridge (WR) of the S Pattern and the southerly Flow (SF) Region of the Multiple (M) tropical cyclone Pattern. Both of these situations involve recurving storms. Medium to high degree of difficulty is found for 72 h forecasts in the North-Oriented Regions of the G and North-oriented (N) Patterns, the Northerly Flow (NF) Region of the M Pattern, and the Accelerating Westerlies (AW) Region of the N Pattern. Small sample sizes for storms in the S/AW and G/AW Patterns/Regions prevent the determination of a degree of difficulty.

The second objective of this thesis was to demonstrate that JTWC official forecasts for storms in each Pattern/Region combination had statistically significant skill when

measured against the no-skill forecasts of the operational CLIPER. The number of independent forecasts in each of the homogenous JTWC versus CLIPER comparisons was estimated assuming that forecasts separated by at least 30 h are independent, which typically reduced the number of cases by a factor of about four. Using a two-sided t-test with a 95% confidence level, only the JTWC forecasts in the S/DR and N/NO Pattern/Region combination had statistically significant skill. The JTWC forecasts in all of the other Patterns and Regions were classified as having undetermined skill because the mean FTE differences were too small for the standard deviations of the JTWC and CLIPER FTEs, or the sample sizes were simply too small to justify a skill/no skill determination at the 95% confidence level. Since the JTWC forecasts within the S/DR and N/NO Patterns/Regions comprise nearly 77% of the five-year sample, the implication is that JTWC has demonstrated skill when compared to CLIPER except for certain Pattern/Region combinations that contain 23% of the forecasts. These no-skill or undetermined skill forecasts ***are*** situations in which an opportunity exists for improvement by JTWC forecasters. As the sample sizes increase, more JTWC forecasts in the Patterns/Regions may become statistically significant. Even if the improvements of the JTWC forecasts relative to CLIPER are not statistically significant, it is <u>practically</u> useful to know that the JTWC forecasts are better than the no-skill CLIPER objective aid in the following Patterns/Regions: S/DR, S/WR, N/NO, N/AW, G/AW, G/DR, and most of the forecast intervals of M/SF.

As transitions occur between the Synoptic Pattern and Region combinations, the degree of difficulty increases and the JTWC forecast skill decreases. That is, JTWC FTEs before, during, and after the four most common recurring transitions (S/DR to N/NO, S/DR

to S/WR, N/NO to N/AW, and N/NO to S/DR) generally do not have statistically significant skill relative to CLIPER. Thus, these nearly 250 transitions during the five years are extremely important because they are situations in which JTWC has opportunities for considerable improvements in track forecasting.

The along-track errors for JTWC forecasts indicate that JTWC track forecasts have a slow bias for all of the Synoptic Pattern/Region combinations. In most of the Pattern/Region combinations, the JTWC cross-track errors have a left of track bias. The Pattern/Region combinations with error ellipses that have dramatically different shapes from the JTWC (ALL) 90% confidence error ellipses were also those with relatively small sample sizes (less than 100), i.e., S/WR, N/AW, M/SF, and M/NF. However, recall that these four Pattern/Region combinations have been identified as Synoptic Environments that are associated with a high degree of difficulty of track forecasting. The orientation of the error ellipses and the length of the major axis provide an indication that storms in these Synoptic Pattern/Region combinations are more difficult to forecast in either the cross-track or along-track direction. Conversely, a minor axis of the error ellipse that is significantly smaller than the major axis indicates that the JTWC forecast is better in the cross-track or along-track direction, as indicated by the orientation of the confidence ellipses. Large error ellipses for storms in certain Pattern/Region combinations provide an indication where JTWC forecasters may be able to improve their performance. When the sample sizes are adequate to reduce the probability of random errors skewing the results, these confidence ellipses for the respective Patterns and Regions could replace the standard circular error distributions currently assumed to apply for all tropical cyclones, regardless of the Synoptic Environment.

Based on this study of five years of JTWC and CLIPER track forecasts in the western North Pacific, the following recommendations are made:

- Classify the 1994 and 1995 tropical cyclone forecasts in terms of the Pattern/Region combinations and include this information with the 1989 to 1993 data base that was used for this thesis. A comparison of the combined seven-year set, the original five-year set, and the new two-year set may detect differences in skill after the JTWC forecasters were introduced to the Systematic Approach in 1994.
- Subsequent research should establish the objective guidance techniques that have skill relative to CLIPER in either a statistical or a practical sense during transitional situations so that JTWC forecasters can improve their performance.
- Ensure that storms that are "off" season are not included in the CLIPER data base, since CLIPER is not valid for those out of season storms.
- Determine distribution curves that better fit the along-track and cross-track errors to improve the specification of track error confidence ellipses.
- Evaluate the skill of the NOGAPS and other objective aid track guidance to determine systematic tendencies/errors as a function of the Synoptic Pattern and Region. It would be extremely valuable to the JTWC forecaster if these guidance techniques could identify transitions between the Synoptic Pattern/Regions. Even the knowledge that a specific guidance technique is incapable of forecasting the transition to a N/NO Pattern/Region until it has

already occurred would be useful, because it would indicate the forecaster must look for other sources of information or "thumb rules" to forecast correctly such a transition.

One of the major conclusions of this study is that JTWC has an opportunity to improve their forecasts during these difficult-to-forecast transition situations. It is expected that a full application of the Systematic Approach (Carr and Elsberry 1994; Carr *et al.* 1995) will assist JTWC to improve tropical cyclone forecast guidance to DOD units and thus minimize the threat of these dangerous tropical cyclones.

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